Liquid Argon Imaging Technology

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Images from liquid Argon

- The liquid Argon Imaging technology: an electronic bubble-chamber, proposed by Carlo Rubbia (CERN-EP/77-08) and supported by INFN over many years of R&D.
- LAr: large sensitive masses, continuously sensitive, self-triggering, 3D views of ionizing events, PID from dE/dx, range and MS.
- The detector also acts as a performing homogeneous calorimeter of very fine granularity: ideal device for rare event detection, such as proton decays and neutrino interactions.
- Argon is inert, not flammable and operates without pressure or moving parts: particularly suitable in difficult environmental conditions (underground experiments)

Present situation

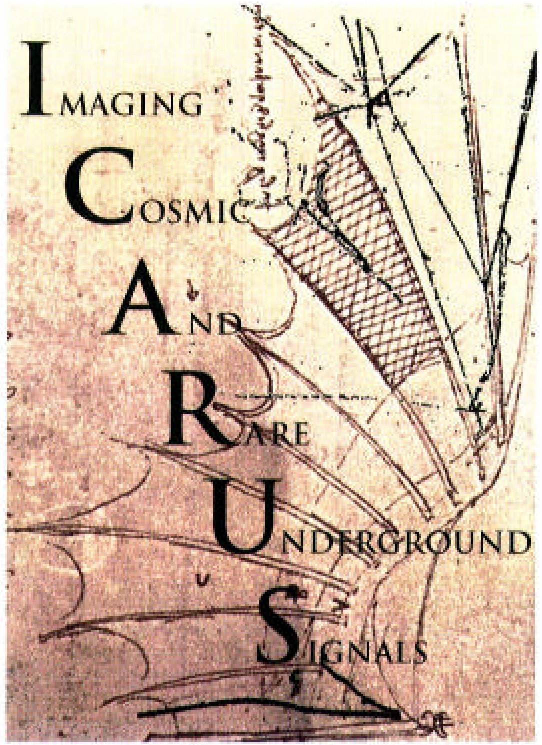
- LAr has recently gained a strong interest in the scientific community, after the:

  - successful operation of the T600 ICARUS detector: the technology is mature
  - realization of the physics potential of high granularity imaging/resolution, for:

    - underground physics: proton decay, solar, atmospheric and supernova neutrinos, ...)
    - short-baseline near detectors: low/medium cross-sections, high-energy precision neutrino physics
    - long-baseline neutrino physics (Super-beams and/or NF)

- One can safely state that:
  - ICARUS at LNGS is the most important milestone for the technology and acts as a full-scale test-bed with a total of 3 kton of liquid Argon in a difficult underground environment

  - extrapolation to very large LAr detector (100-200 kton) is under investigation



ICARUS is...

- a background-free, nucleon decay search experiment
- a solar neutrino experiment
- a supernova watch experiment
- an atmospheric neutrino experiment
- a LBL t and e appearance experiment in the CNGS beam

The ICARUS Collaboration
(25 institutes, about 150 physicists)

ITALY: L'Aquila, LNF, LNGS, Milano, Napoli, Padova, Pavia, Pisa, CNR Torino, Torino Univ., Politec. Milano.
SWITZERLAND: CERN, ETH/Zürich.
CHINA: Academia Sinica Beijing.
POLAND: Univ. of Silesia Katowice, Univ. of Mining and Metallurgy Krakow, Inst. of Nucl. Phys. Krakow, Jagellonian Univ. Krakow, Univ. of Technology Krakow, A.Soltan Inst. for Nucl. Studies Warszawa, Warsaw Univ., Wroclaw Univ.
USA: UCLA Los Angeles.
SPAIN: University of Granada, CIEMAT
RUSSIA: INR Moscow

Liquefied rare gases: basic ideas

Ideal materials for detection of ionizing tracks:

- dense, homogeneous, active target
- do not attach electrons (long drift paths possible in liquid phase)
- high electron mobility (quasi-free drift electrons, not Neon)
- commercially easy to obtain (in particular, liquid Argon)
- can be made very pure and impurities freeze out at low temperature
- inert, not flammable
- Ar constitutes 0.9% of air content

Element	Density (ρ/cm^3)	Energy loss dE/dx (MeV/cm)	Radiation length X_0 (cm)	Collision length λ (cm)	Boiling point @ 1 bar (K)	Electron mobility (cm^2/Vs)	Cost
Neon	1.2	1.4	24	80	27.1	high&low	
Argon	1.4	2.1	14	80	87.3	500	€
Krypton	2.4	3.0	4.9	29	120	1200	€€
Xenon	3.0	3.8	2.8	34	165	2200	€€€

Liquid Argon TPC properties

- High density, heavy ionization medium
  - ρ = 1.4 g/cm^3, X_0=14 cm, λ_{int} = 80 cm
- Very high resolution detector
  - 3D image 3 x 3 x 0.6 mm^3 (400 ns sampling)
- Continuously sensitive
- Self-triggering or through prompt scintillation light
- Stable and safe
  - Inert gas/liquid
  - High thermal inertia (230 MJ/m^3)
- Relatively cheap detector
  - Liquid argon is cheap, it is only "stored" in the experiment
  - TPC: # of channels proportional to surface

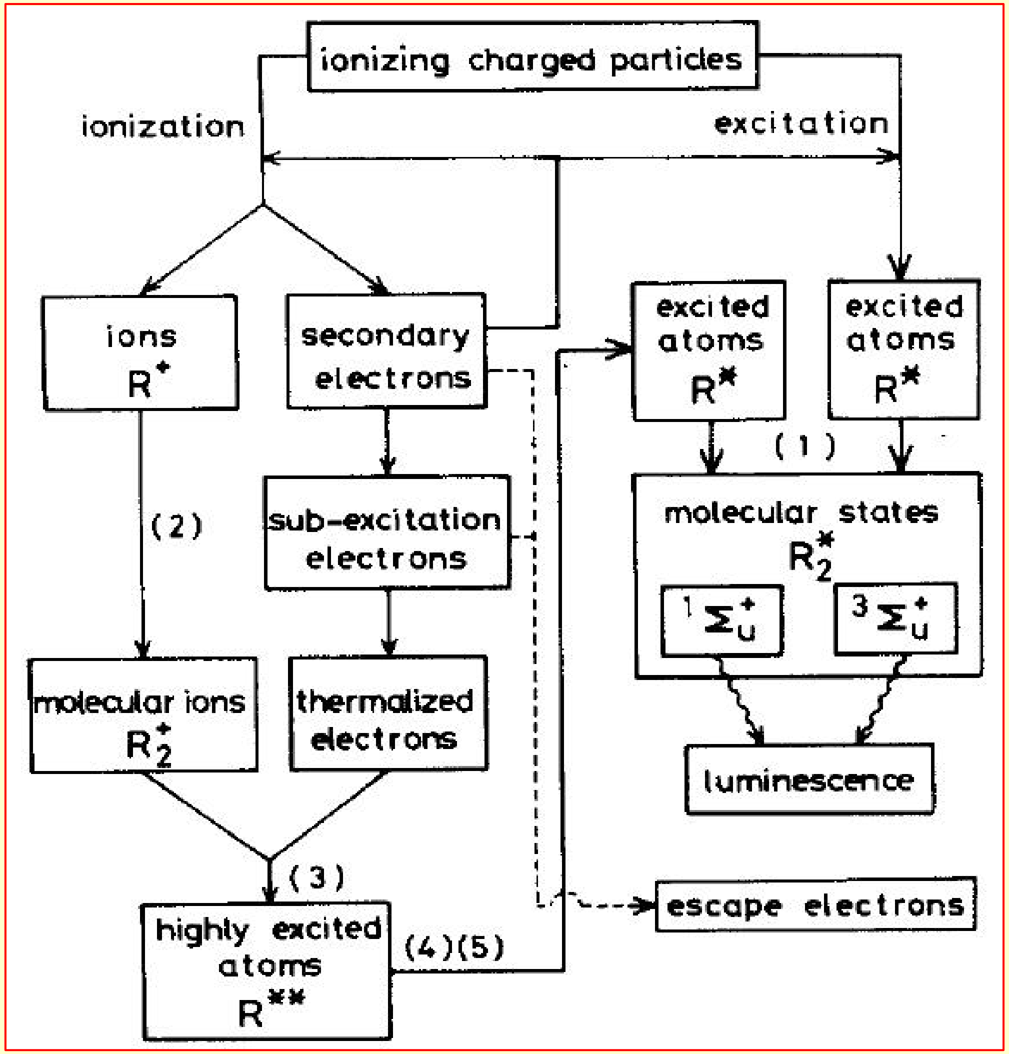
- Cryogenic temperature
  - T = 88 K at 1 bar
- High purity required for long-drift time
  - 0.1 ppb of O_2 equivalent for 3 ms drift
- No signal amplification in liquid
  - 1 m.i.p. over 3 mm yields 20000 electrons
  - equivalent noise charge 1200 electrons

Cryogenic plant

Argon purification

Low noise electronics

Processes induced by charged particles in liquid Argon



M. Suzuki et al., NIM 192 (1982) 565

When a charged particle traverses a medium:

- Ionization process
- Scintillation (luminescence)
  - UV spectrum (λ=128 mn)
  - Not energetic enough to further ionize (Argon is transparent)
  - Rayleigh-scattering
- Cerenkov light (for fast particle)

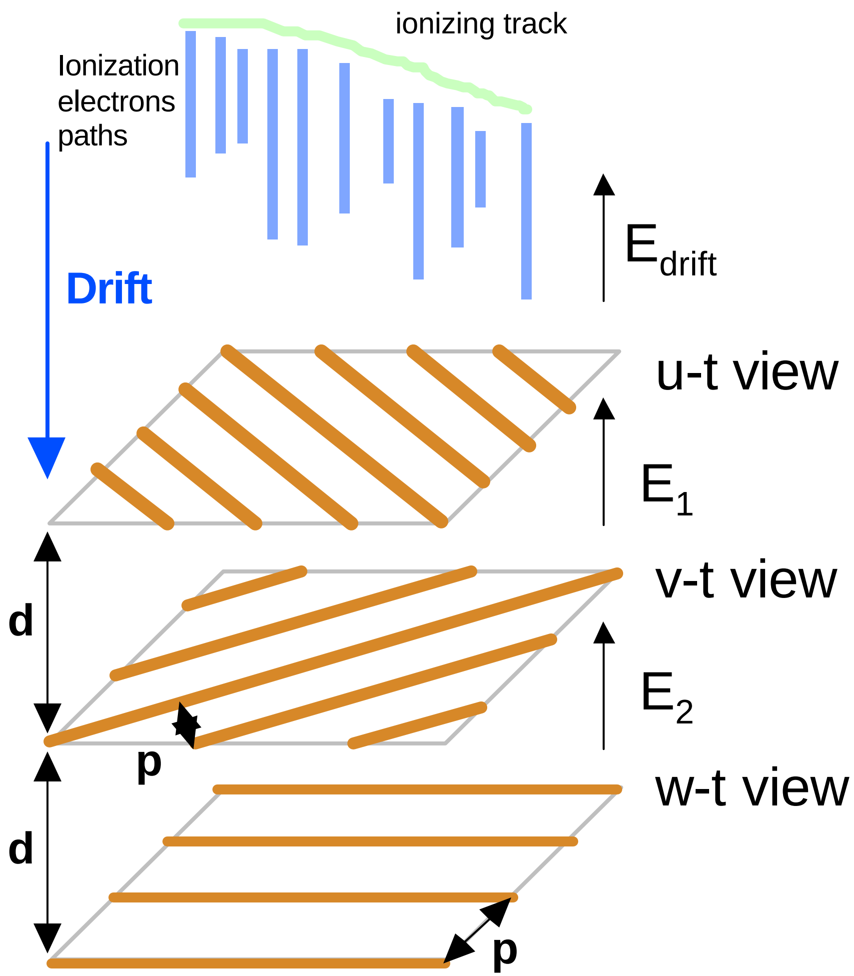
UV light

Charge

Cerenkov light (if β>1/n)

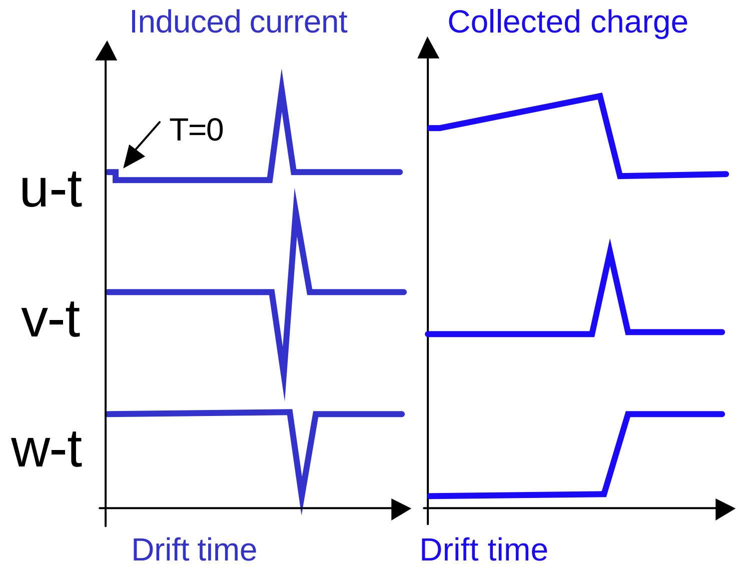
A small addition (˜ 500ppm) of Xenon shifts the UV radiation to 178 nm

Charge readout and imaging

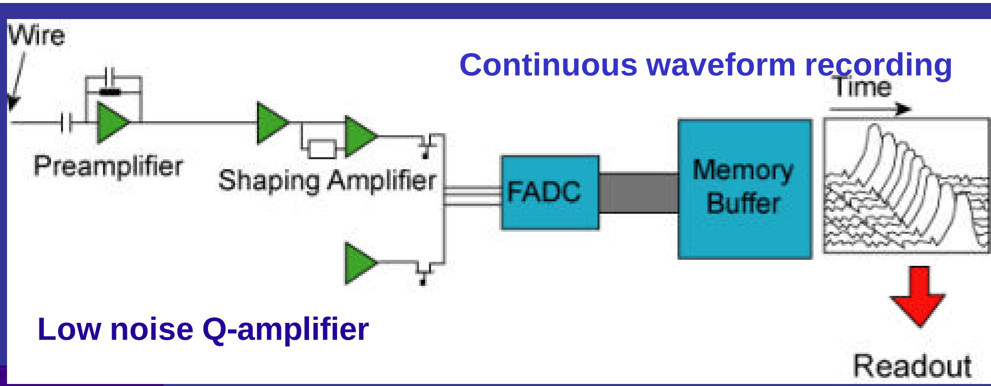


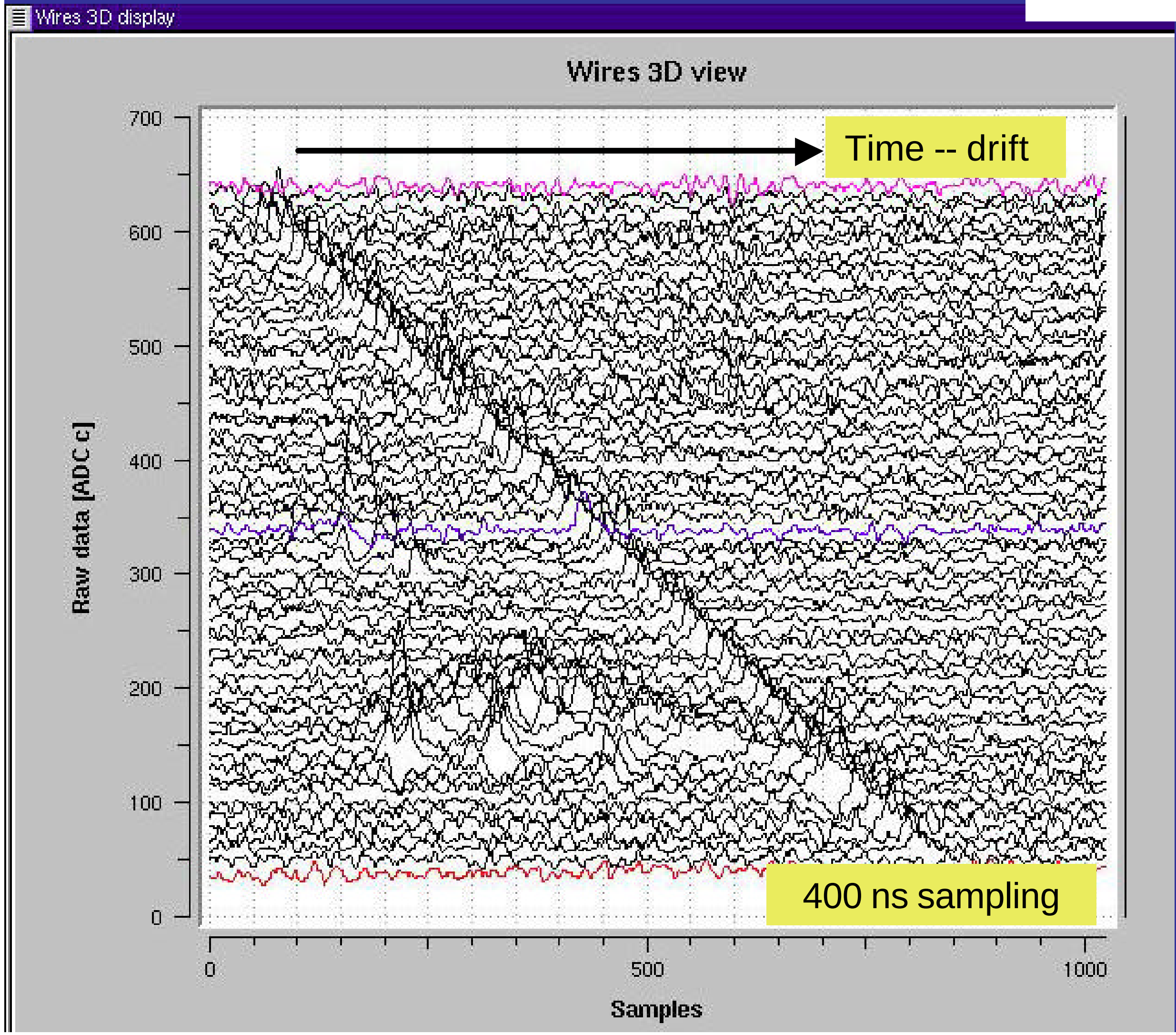
Yield ~ 6000 electrons/mm
~ 1 fc/mm

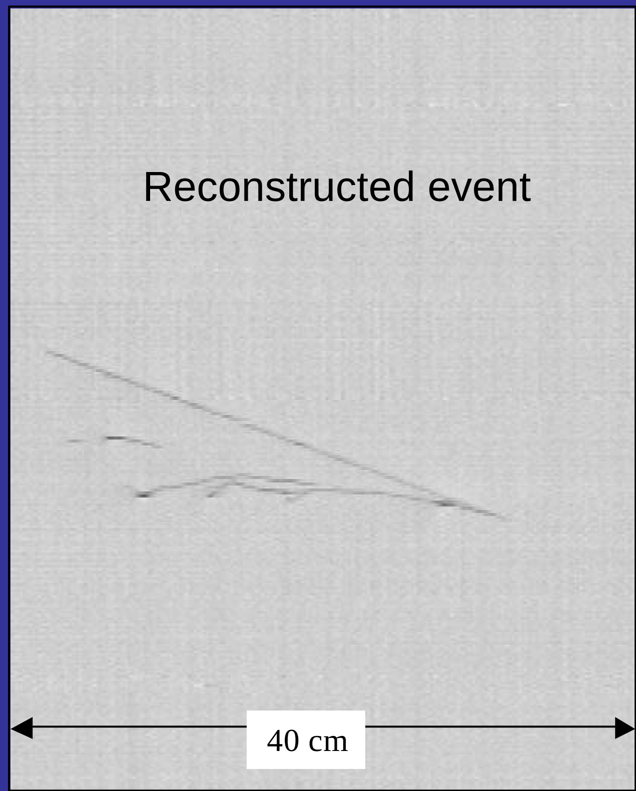
In the ICARUS T600 : E_{drift} = 500 V/cm
p = 3 mm
d = 3 mm
r = 0.1mm



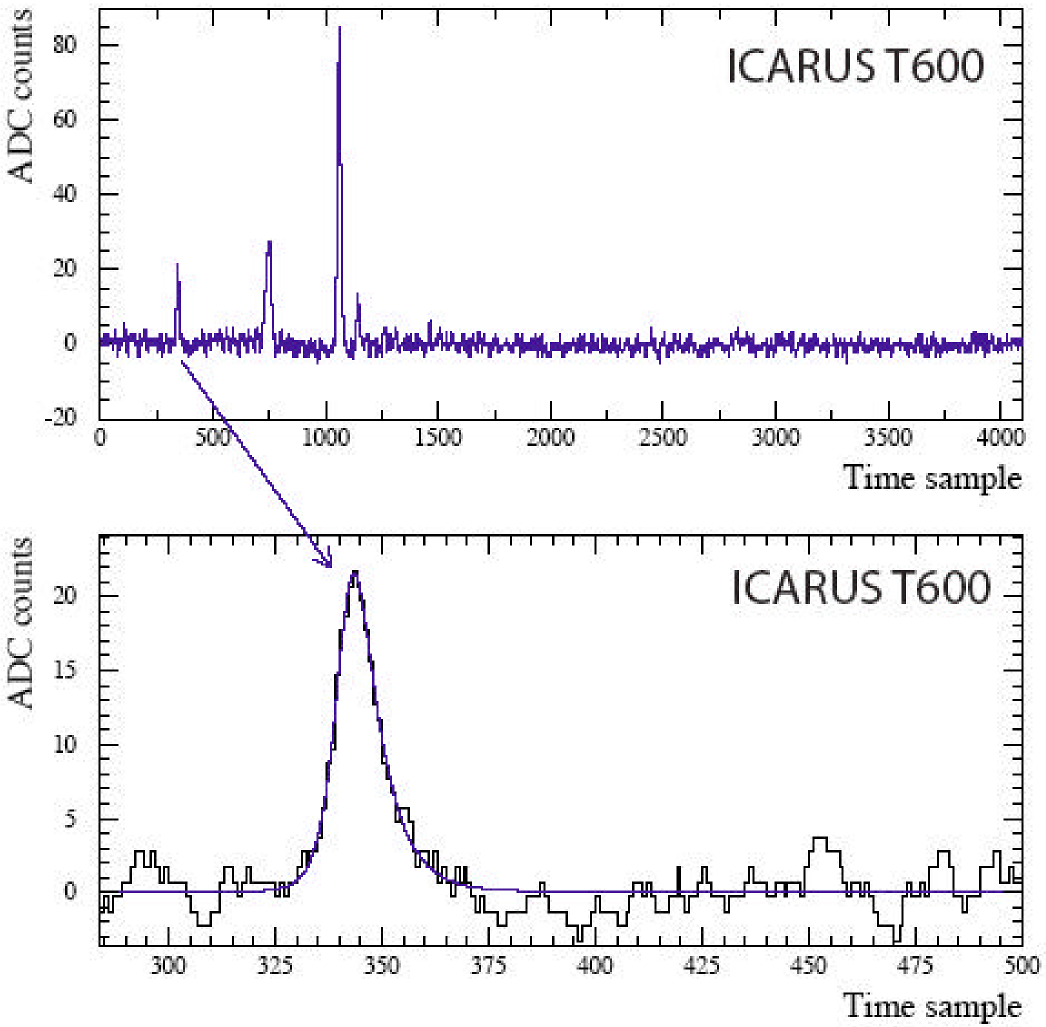
Principle of signal recording







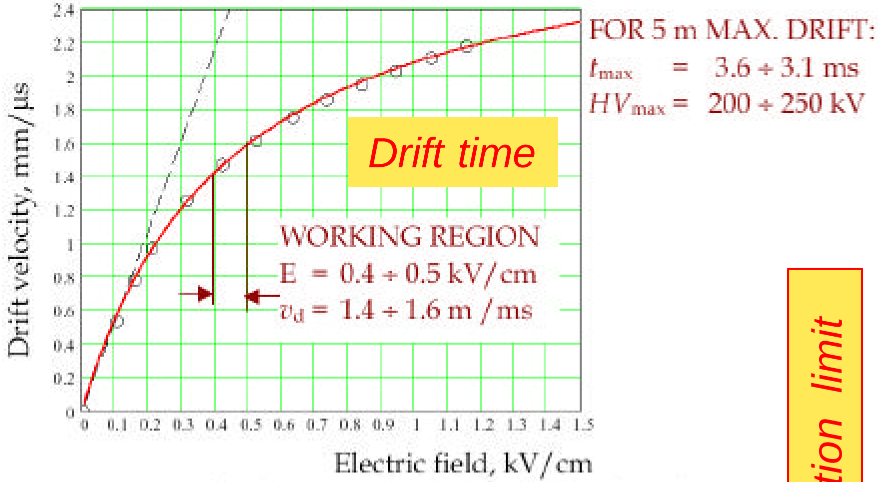
Single wire signal



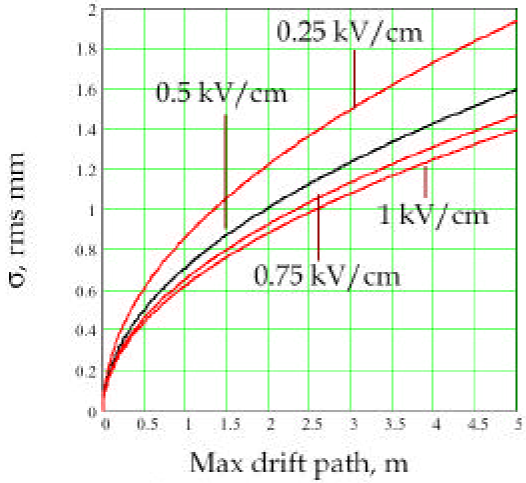
Fit function:

$$f(t) = B + A\frac{e^{-\frac{t-t_0}{\tau_1}}}{1+e^{-\frac{t-t_0}{\tau_2}}}$$

Electron drift properties in liquid Argon



Drift velocity versus electric field in liquid argon



Longitudinal rms diffusion spread versus drift paths at different electric field intensities

R.m.s. diffusion speed

$$\sigma_D = \sqrt{2 \cdot D \cdot \frac{x}{v_d}}$$

$D = 4.06\ \mathrm{cm^2/s}$

$\sigma_D = 0.9\ \mathrm{mm} \cdot \sqrt{T_D[\mathrm{ms}]}$

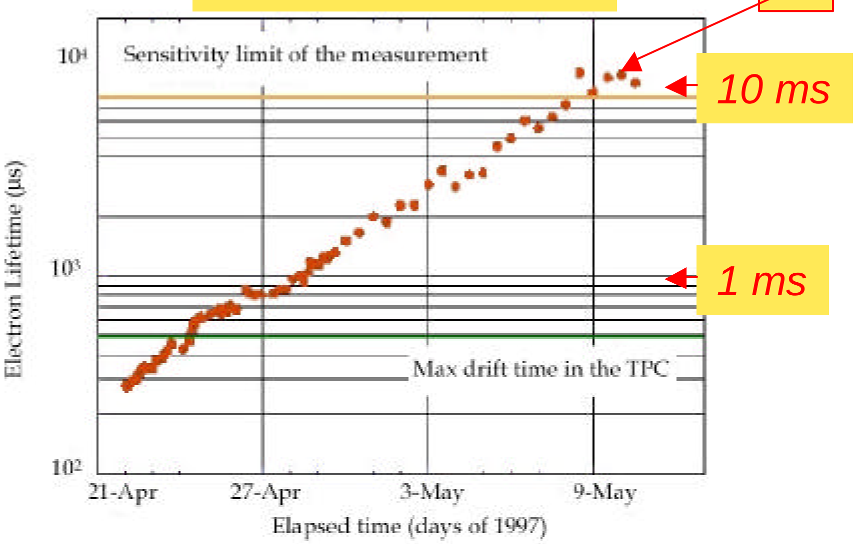
Longitudinal rms diffusion spread at 0.5 kV/cm

Average $\langle\sigma_D\rangle$ = 1.1 mm

Maximum σ_{Dmax} = 1.6 mm

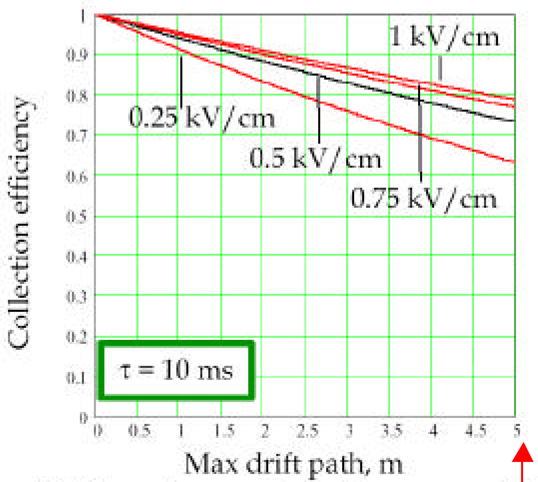
Electron lifetime, ms

Detection limit

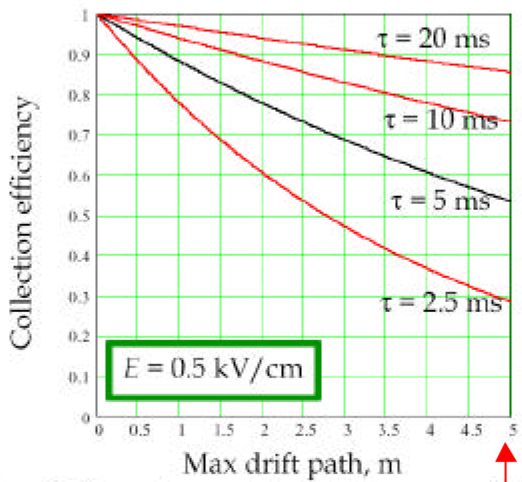


Purification rate for the 50L TPC

Drift path, m

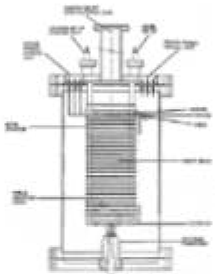


Drifting charge attenuation versus drift paths at different electric field intensities (τ = 10 ms)



Drifting charge attenuation versus drift path at different electron lifetimes (E = 0.5 kV/cm)

The path to massive liquid Argon detectors



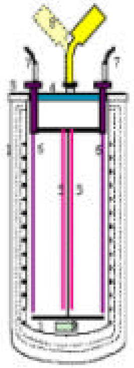
24 cm drift wires chamber

1

1987: First LAr TPC. Proof of principle. Measurements of TPC performances.

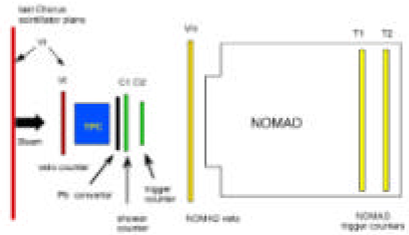
2

3 ton prototype



1991-1995: First demonstration of the LAr TPC on large masses. Measurement of the TPC performances. TMG doping.

Laboratory work



50 litres prototype
1.4 m drift chamber

3

1997-1999: Neutrino beam events measurements. Readout electronics optimization. MLPB development and study. 1.4 m drift test.

4

10 m^3 industrial prototype

1999-2000: Test of final industrial solutions for the wire chamber mechanics and readout electronics.

T600 detector

2001: First T600 module

5

Cooperation with industry

Basic R&D is completed. However, still working on improvements. e.g.:

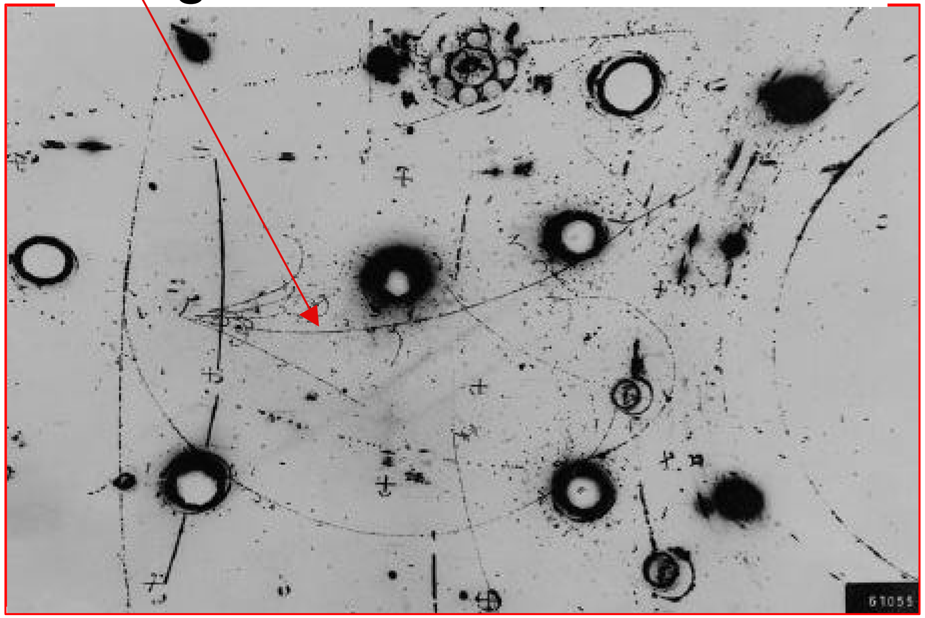
TPC prototype for UV-laser calibration and monitoring of LAr purity

Thirty years of progress........

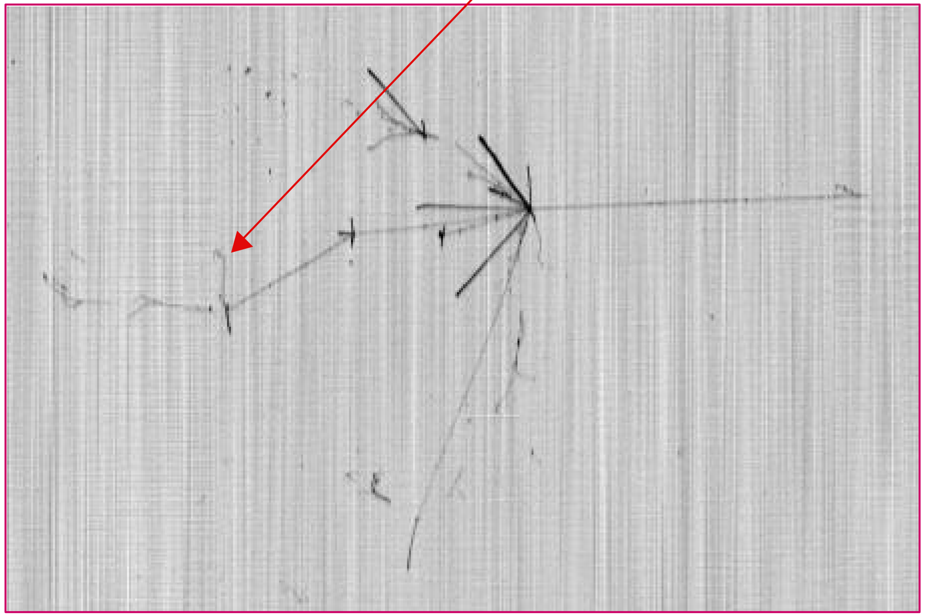
Bubble diameter ~ 3 mm (diffraction limited)

Bubble size ~ 3x3x0.2 mm³

Gargamelle bubble chamber



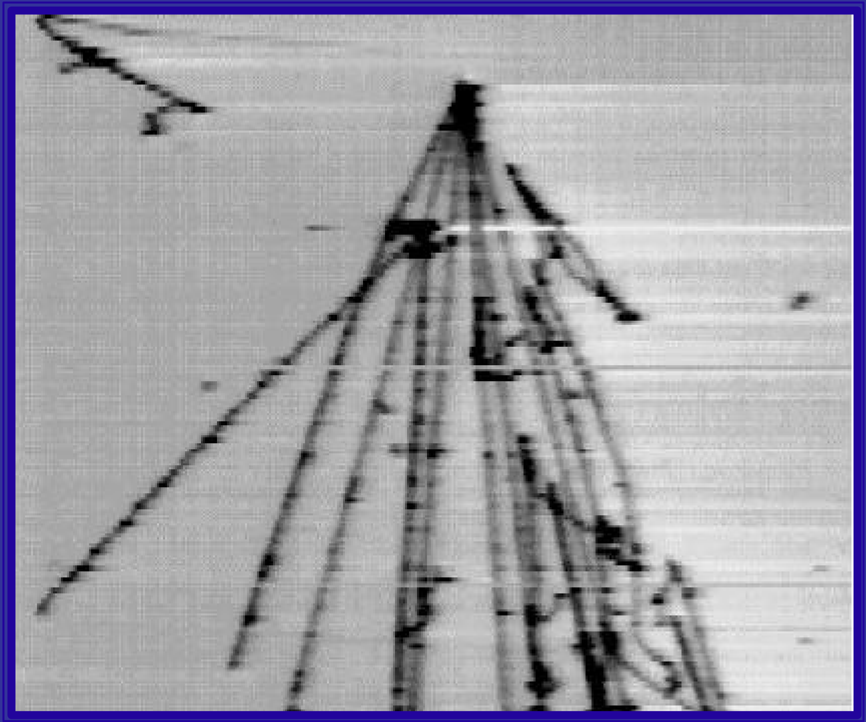
ICARUS electronic chamber



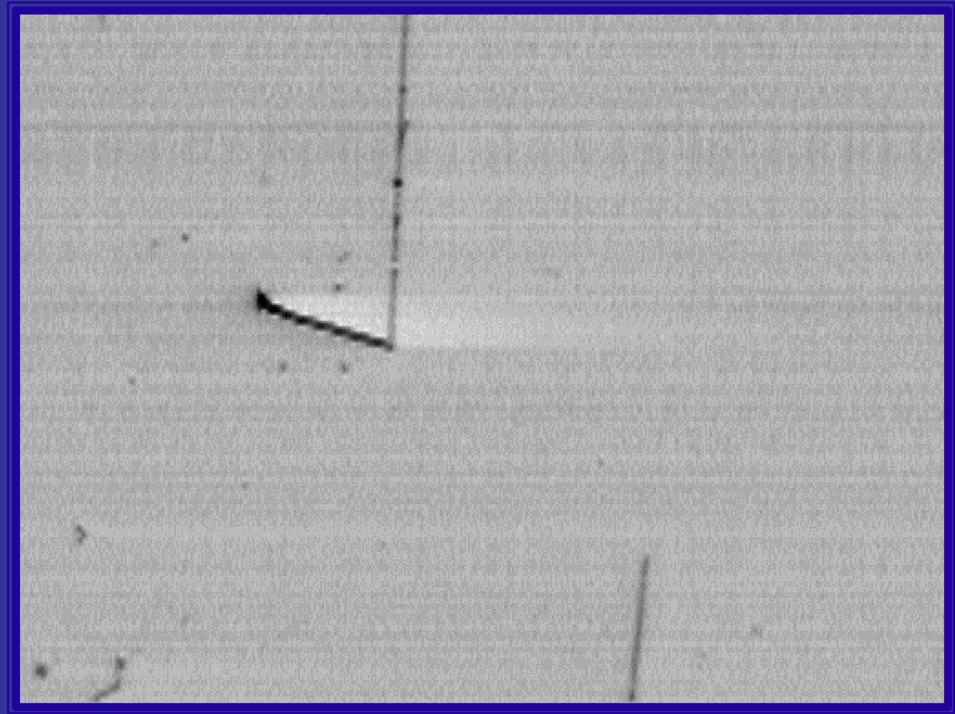
Medium	*Heavy freon*	
Sensitive mass	3.0	ton
Density	1.5	g/cm^3
Radiation length	11.0	cm
Collision length	49.5	cm
dE/dx	2.3	MeV/cm

Medium	*Liquid Argon*	
Sensitive mass	Many ktons	
Density	1.4	g/cm^3
Radiation length	14.0	cm
Collision length	54.8	cm
dE/dx	2.1	MeV/cm

50 l prototype in the CERN WANF neutrino beam

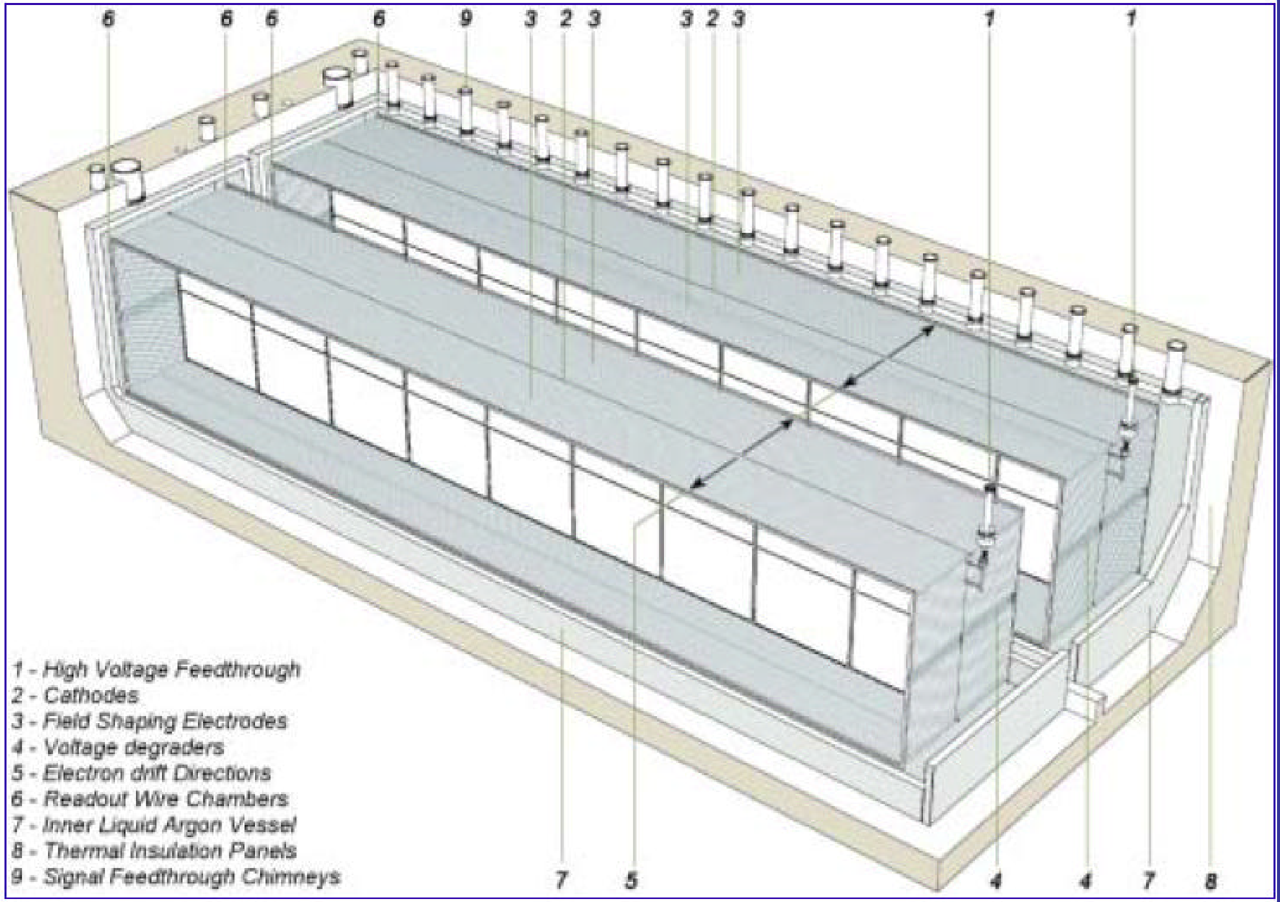


$n_m + X \rightarrow m^- + many\ \ prongs$



$n_m + n \rightarrow m^- + p$

The T600 module

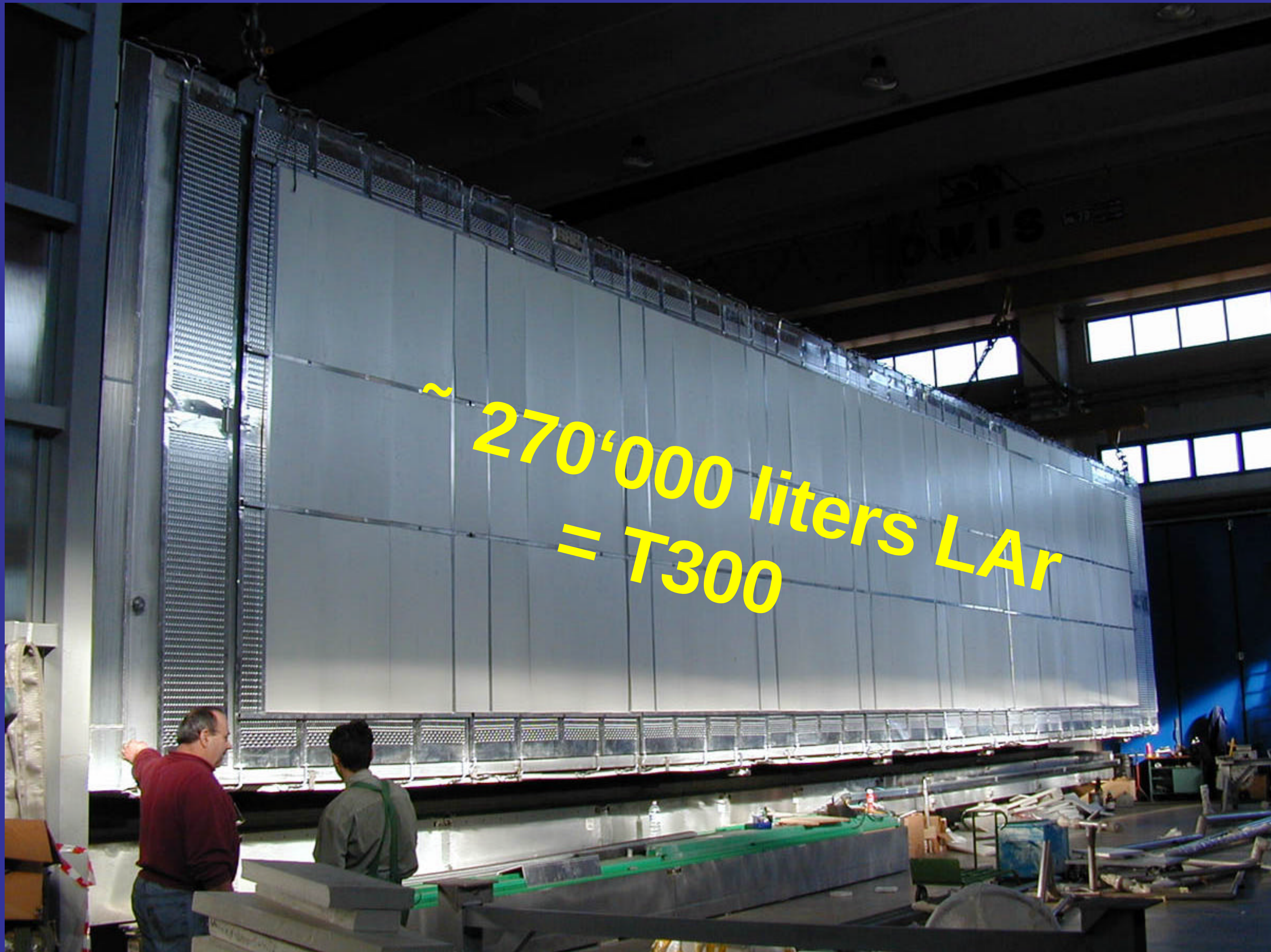


- Two separate containers
- inner volume/cont. = **3.6 x 3.9 x 19.6 m^3**
- 4 wire chambers with 3 readout planes at 0°, ±60°
- (two chambers/container) ~ 54000 wires
- Maximum drift = 1.5 m
  HV = -75 kV @ 0.5 kV/cm
- Scintillation light readout with 8” VUV sensitive PMTs

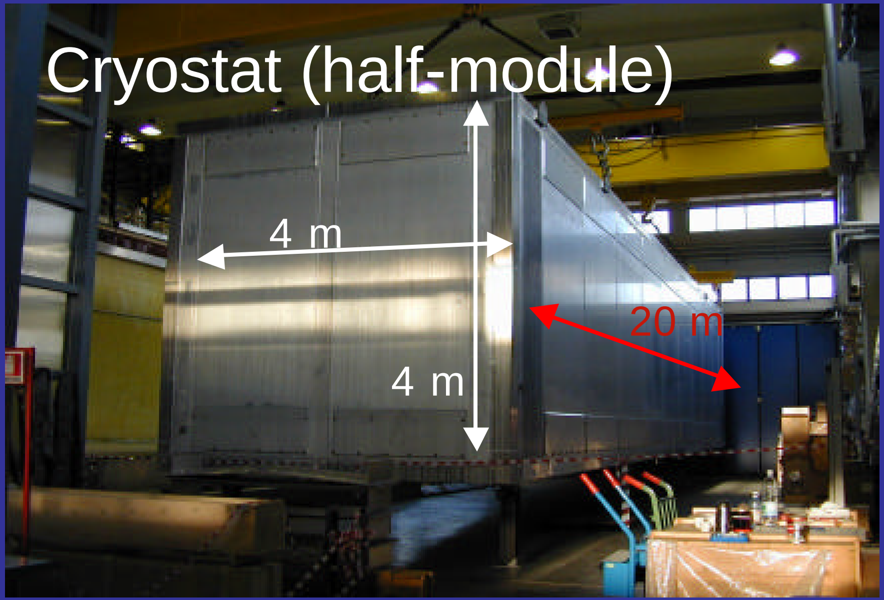
- The detector is completely assembled and equipped with the inner detectors, since nearly two years !

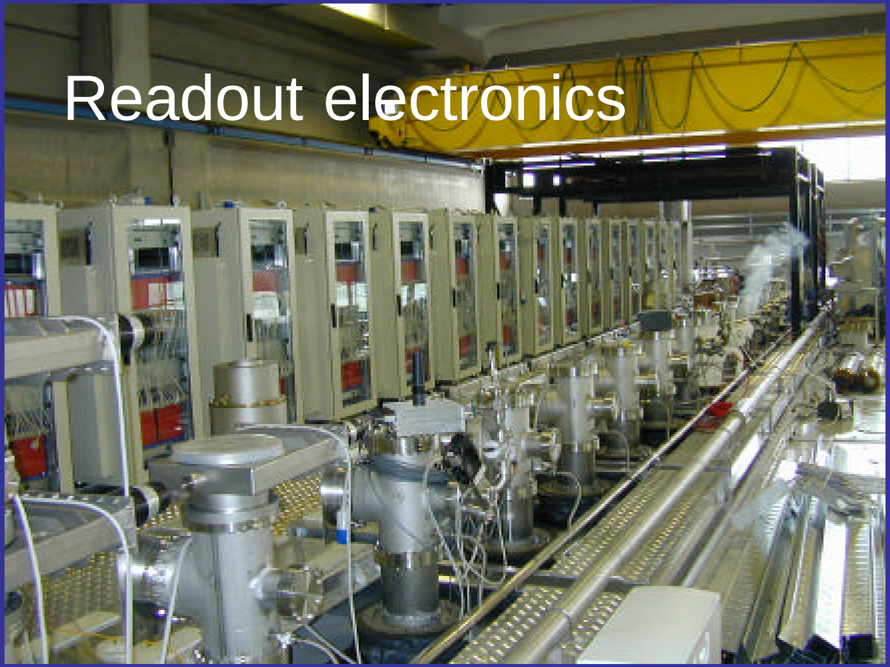
Design, construction and tests of the ICARUS T600 detector.
To appear on N.I.M.

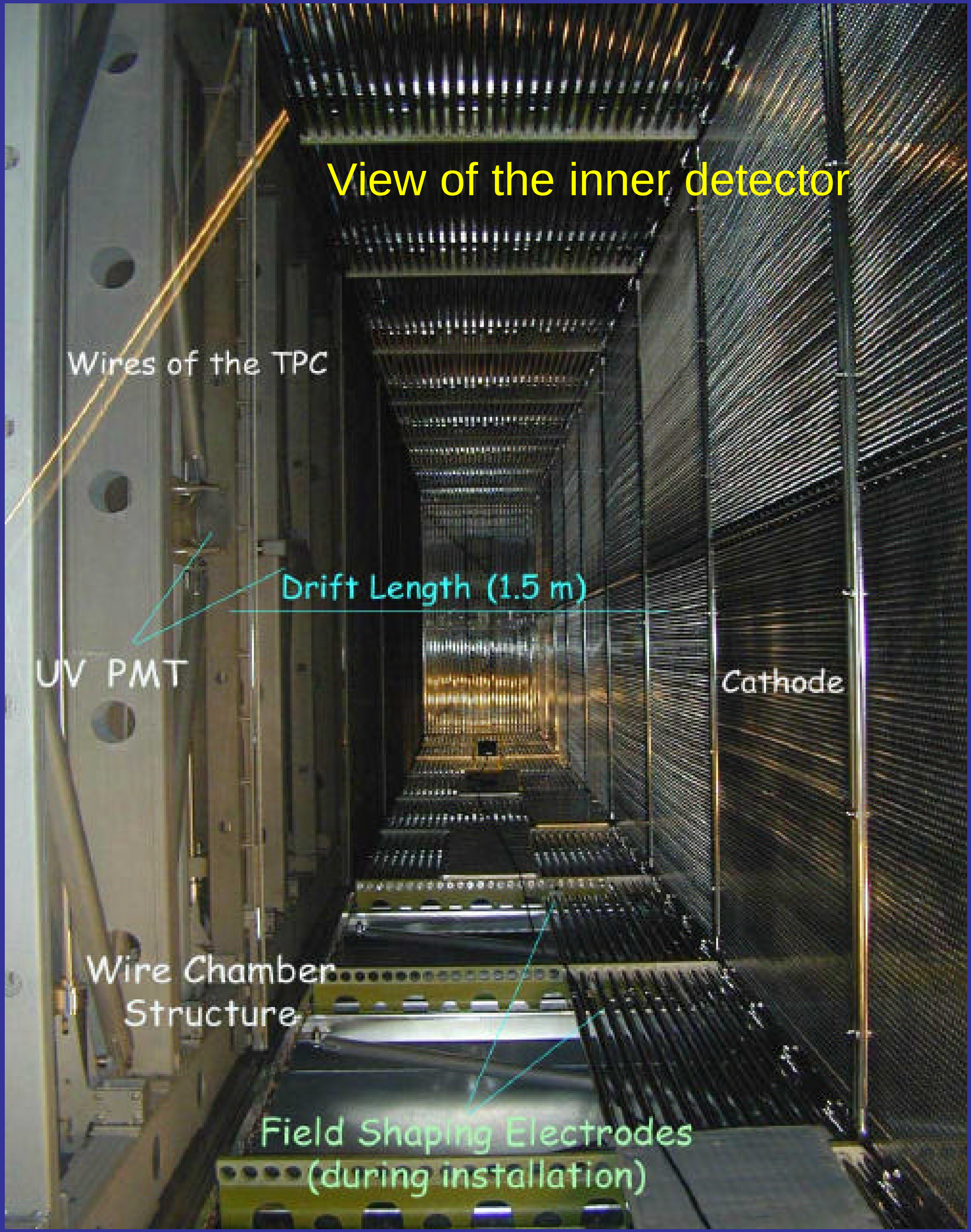
First T300 cryostat during construction (2001)

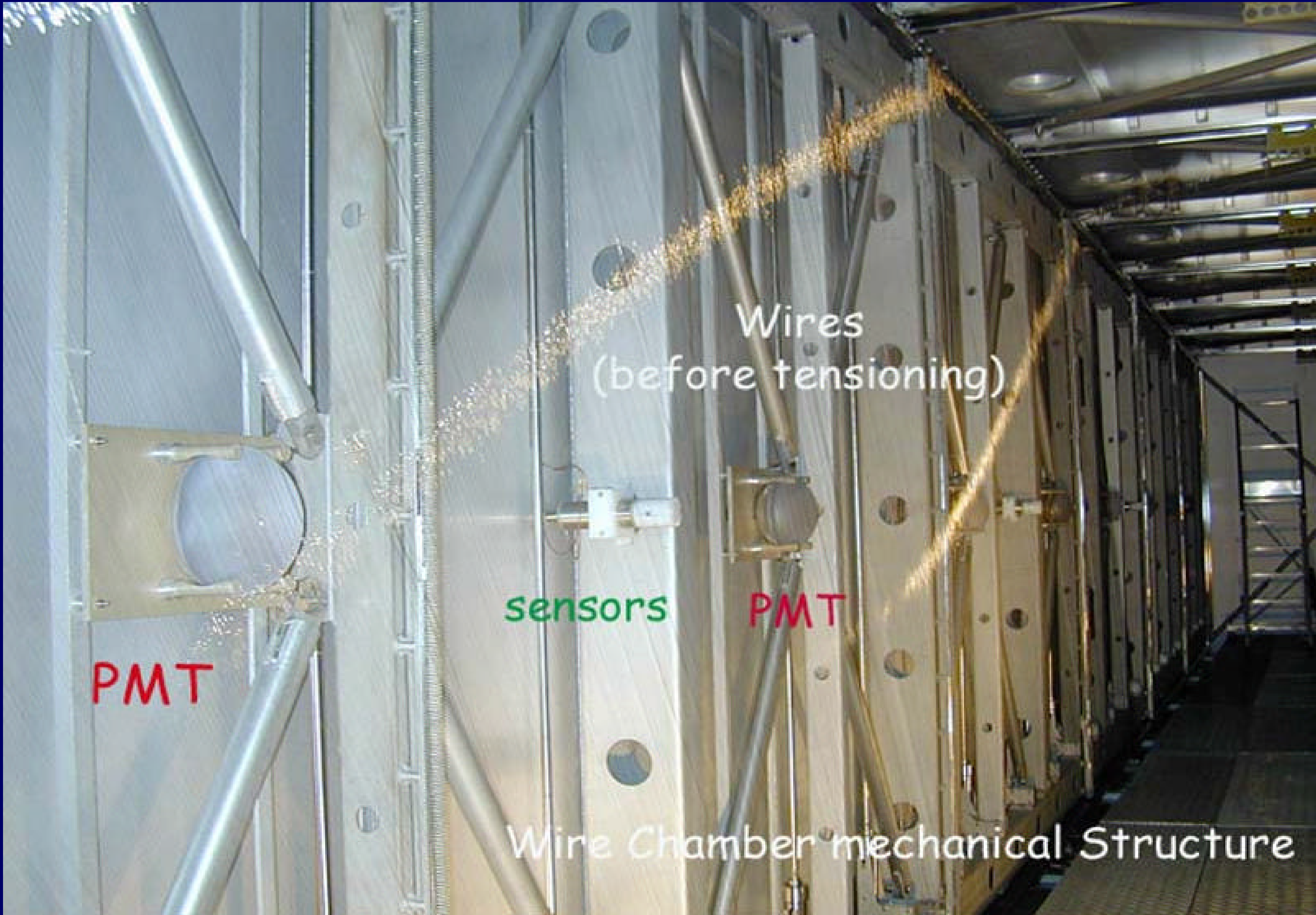


ICARUS T300 prototype





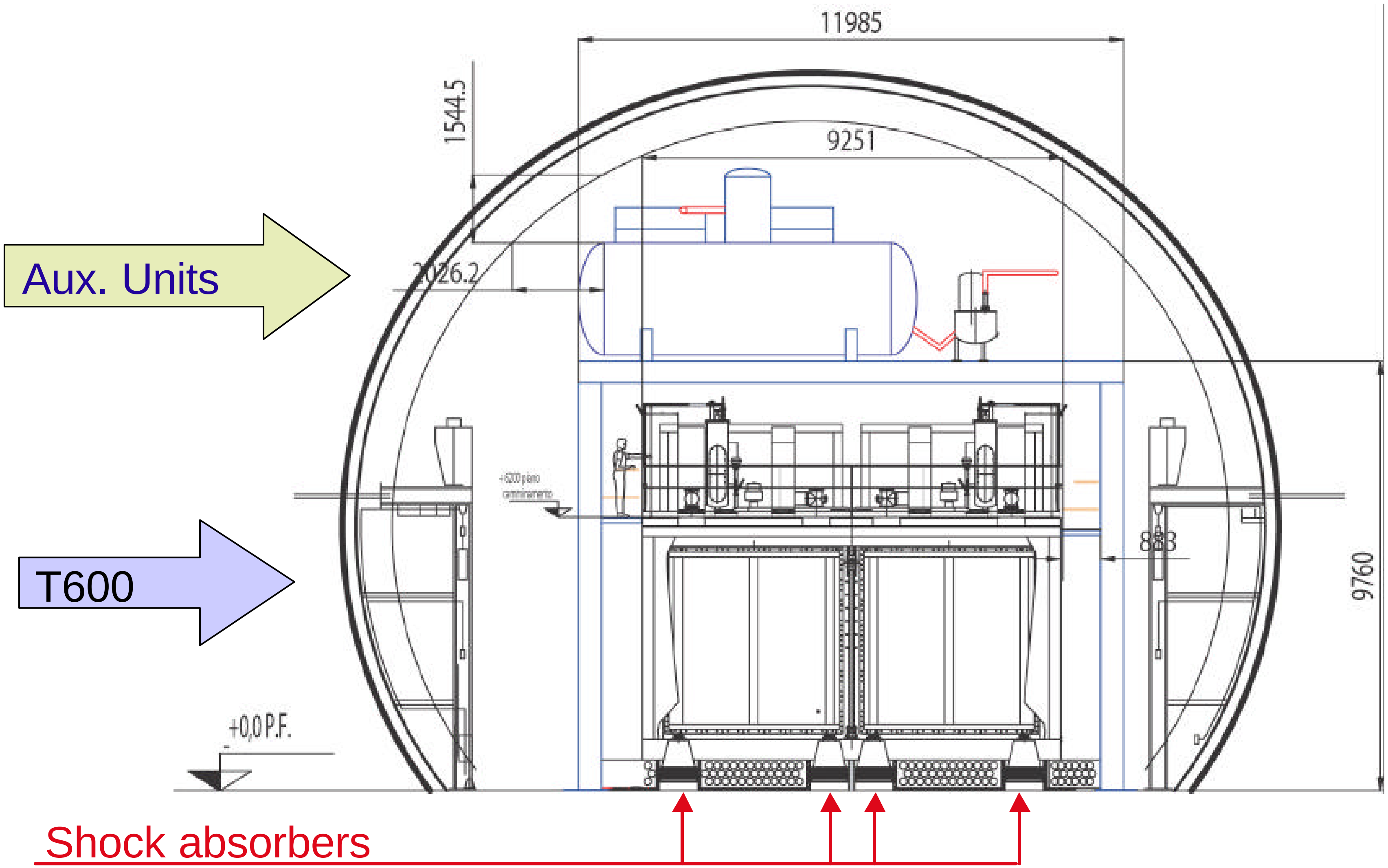




Wires
(before tensioning)
sensors
PMT
PMT
Wire Chamber mechanical Structure

LNGS Hall B

First step: T600 installation at LNGS



The T600 installation procedure of the T600 in Hall B has started:

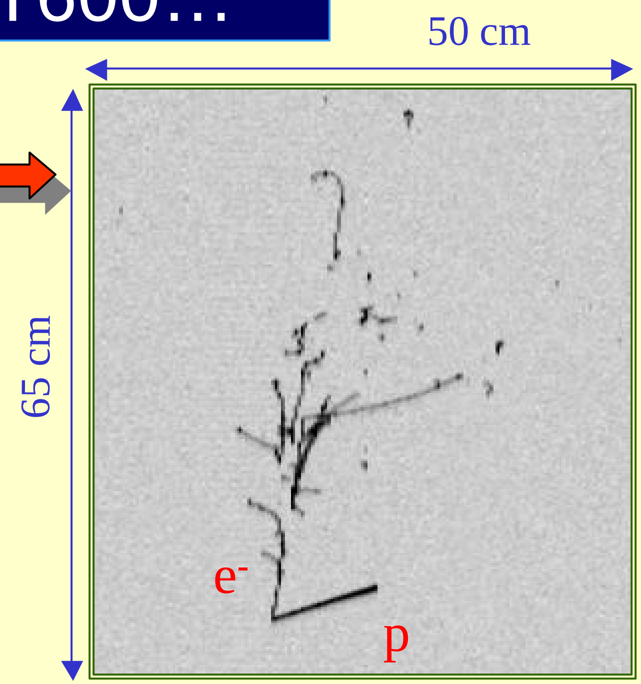
• contract for transportation (Pavia→ LNGS) adjudicated

• interventions on the floor for safety requirements (Government Comm.ner) being defined

• goal: T600 in Hall B by mid 2004 (parking lot position); infrastructure & support structure completed by end 2004; data taking with cosmic events by mid 2005

Soon, physics with the T600…

In 1 year of T600 running ICARUS will collect about 100 events of this quality (in presence of oscillations)



BG free detection of solar neutrino events (E>8MeV)

Solar ν events per year in T600

Elastic	Fermi	Gamow-Teller
38	165	295

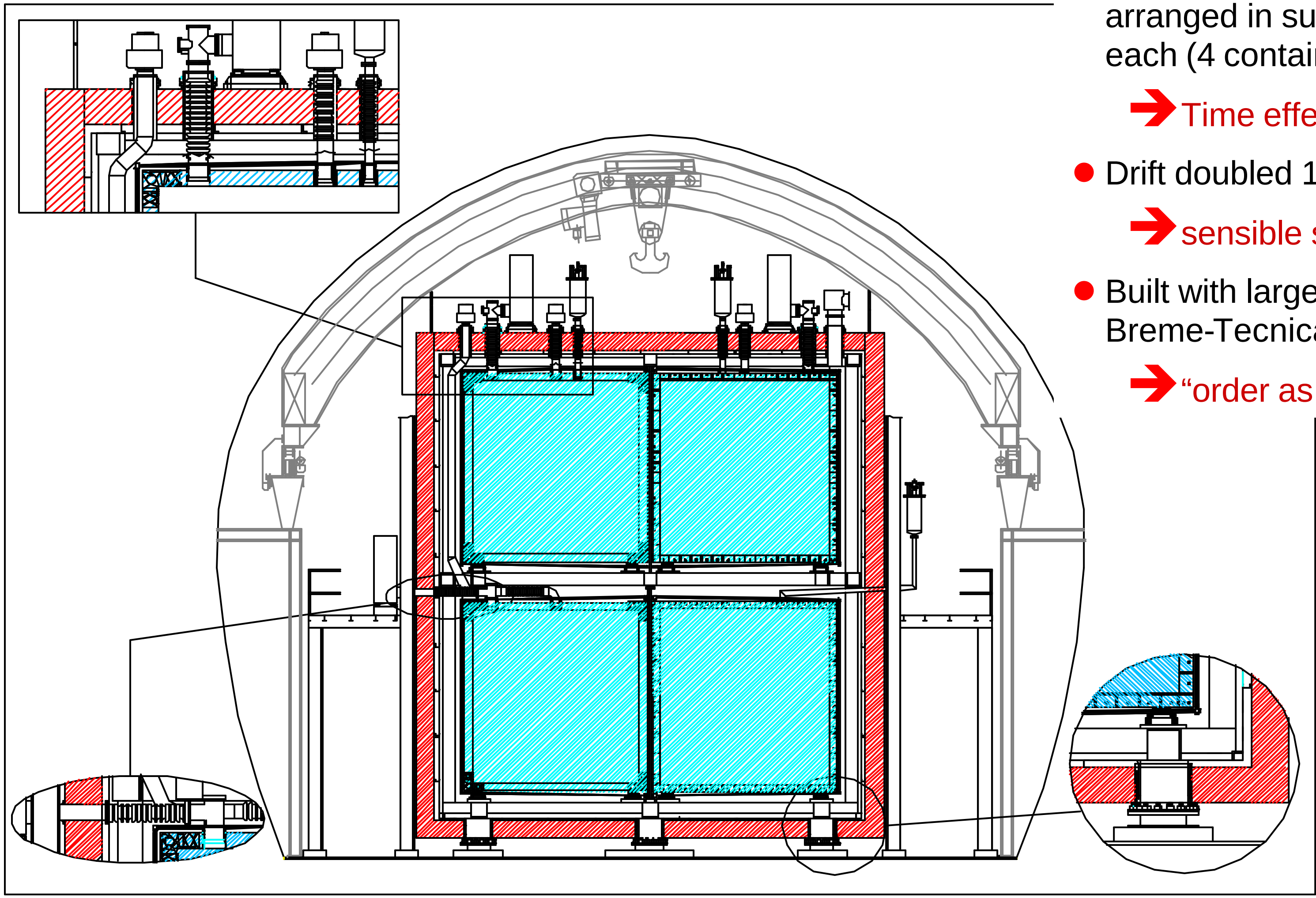
Search for proton decay event topologies

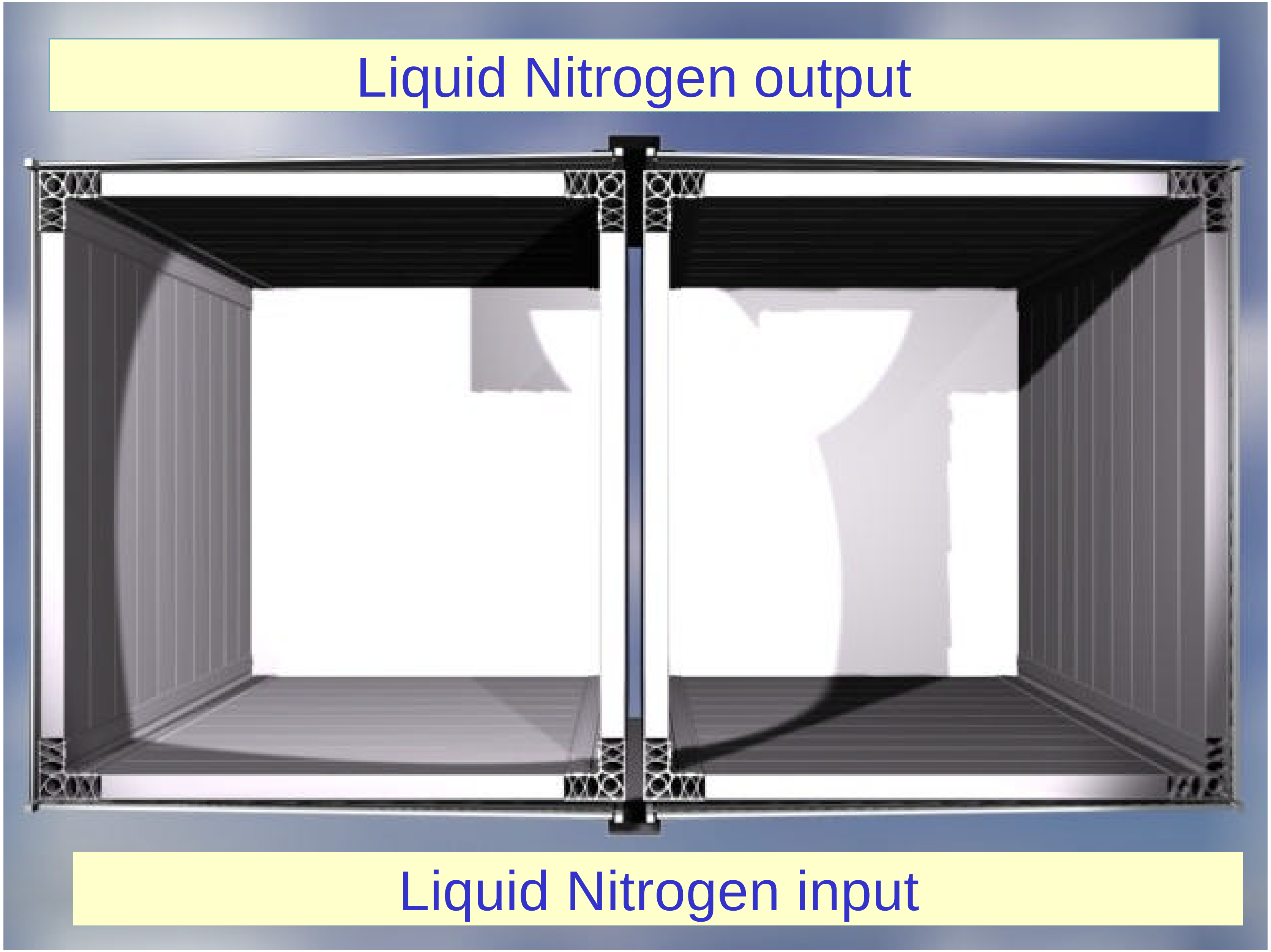
Supernova observatory

..and more: learn about a new technology for astroparticle physics

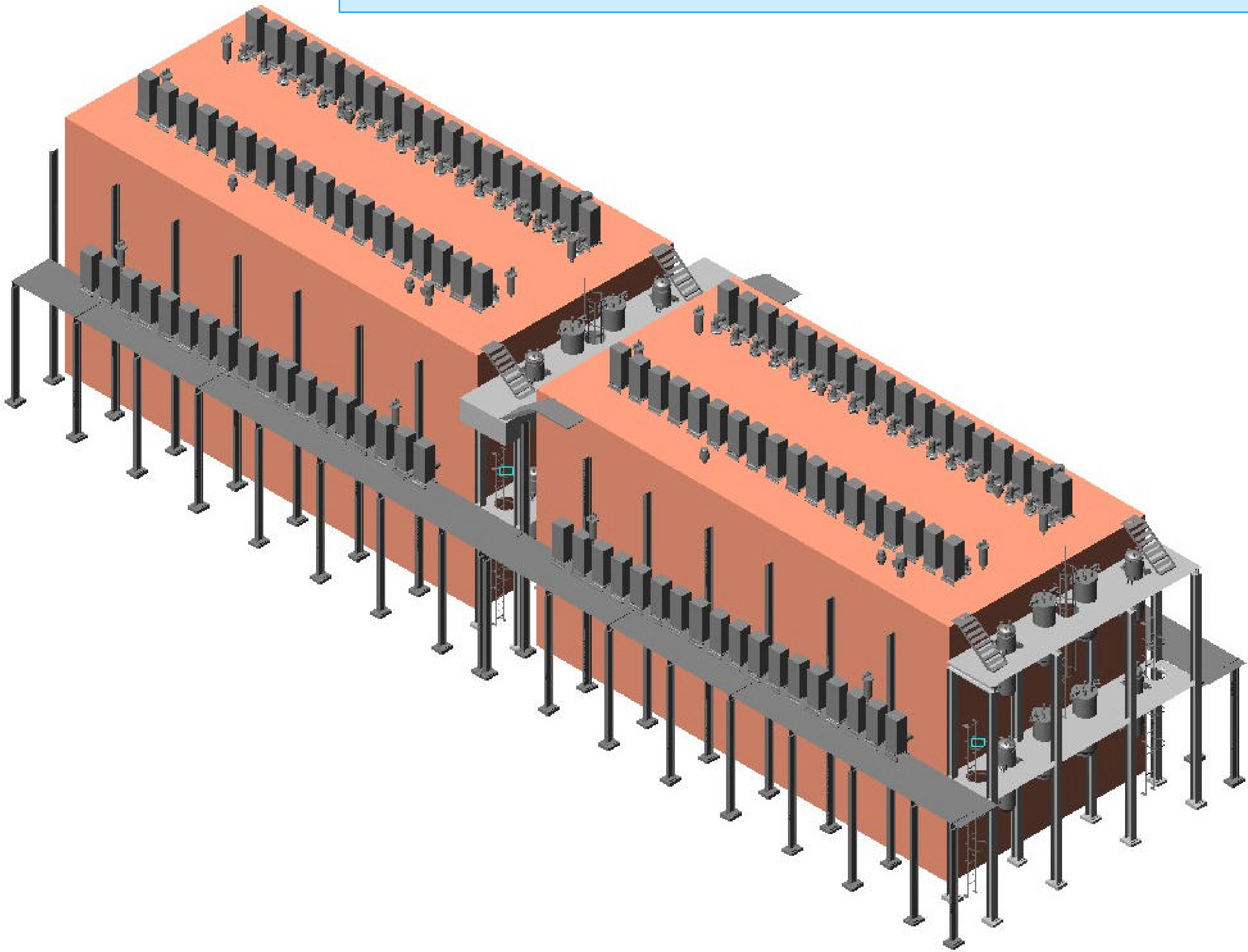
The ICARUS T1200 "Unit"

- Based on cloning the present T300 dewars
  - ➔ A cost-effective solution given tunnel access conditions
- Preassembled modules outside the tunnel are arranged in super-modules of about 1200 ton each (4 containers)
  - ➔ Time effective solution (parallelizable)
- Drift doubled 1.5 m ➔ 3 m
  - ➔ sensible solution given past experience
- Built with large industrial support (AirLiquide, Breme-Tecnica, Galli-Morelli, CAEN, …)
  - ➔ "order as many as you need" solution




Liquid Nitrogen output
Liquid Nitrogen input

ICARUS T1200 + T1200



T600 detector performance (surface test run)

- Technical run at surface in 2001: assess the maturity of large scale LAr imaging TPC. Main phases:

  clean-up (vacuum) 10 days, cool-down 15 days, LAr filling 15 days, debug and data-taking 68 days.

- 18 m long track (request by Scientific Committees) plus a large number of cosmic-ray events:

  about 28000 triggers with different topologies

  4.5 TB of data, 200 MB/event.

- Valuable data: check performance of a such large scale detector. Found that:

  results of the same quantitative quality as those obtained with small prototypes (e.g. 3 ton, 50 liter, ...) are achieved with a 300 ton device.

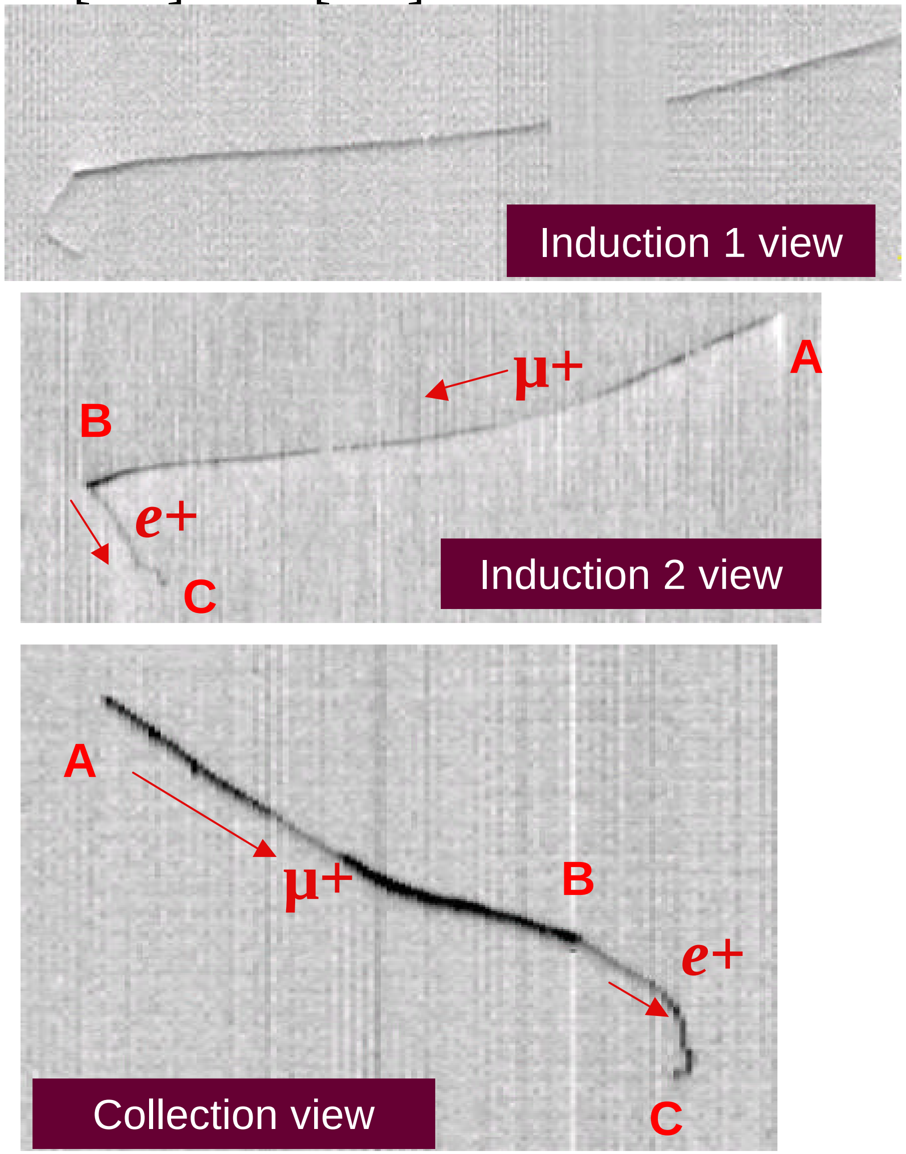
- Several papers published with test data →

Analysis of the liquid Argon purity in the ICARUS T600 TPC.
N.I.M. A516 (2004) 68.

Study of the electron recombination in liquid Argon in the ICARUS TPC.
To appear on N.I.M.

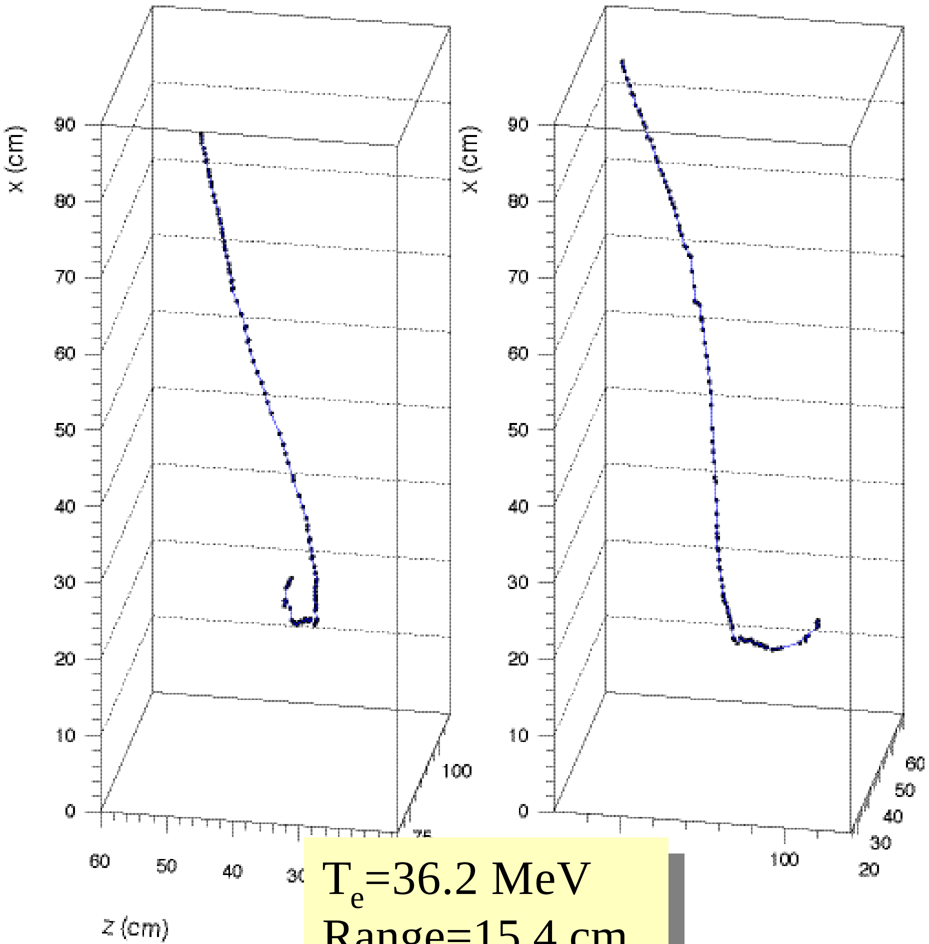
3D reconstruction stopping muon

$m^{+}[AB] \rightarrow e^{+}[BC]$



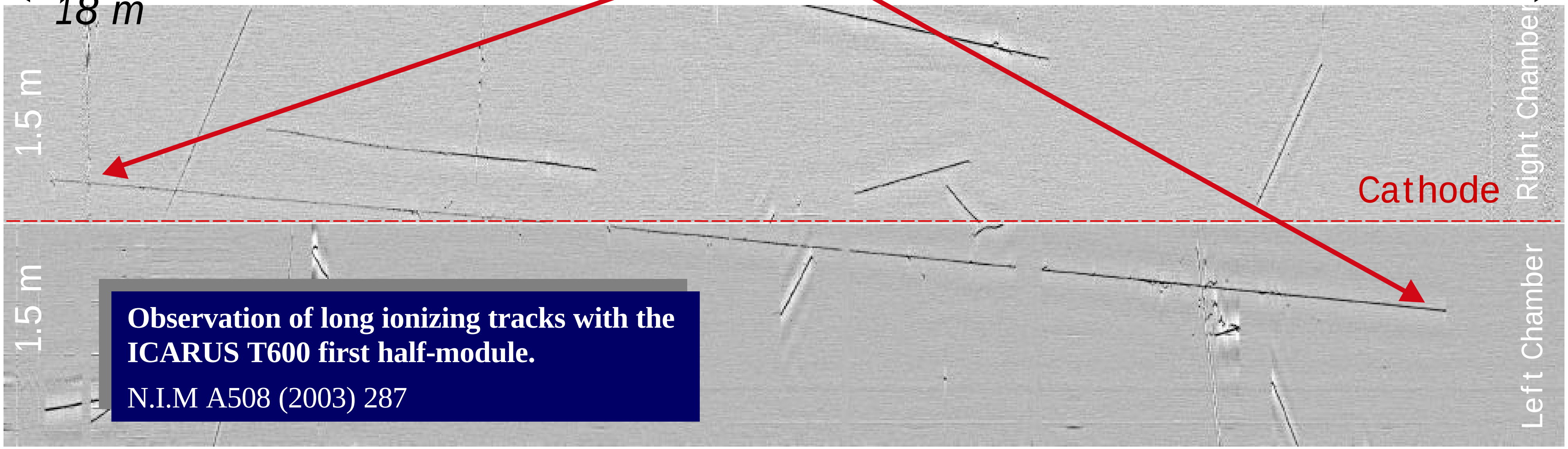
Measurement of the m decay spectrum with the ICARUS liquid Argon TPC.

Eur. Phys. Journ. C (2004). DOI 10.1140/epjc/s2004-01597-7

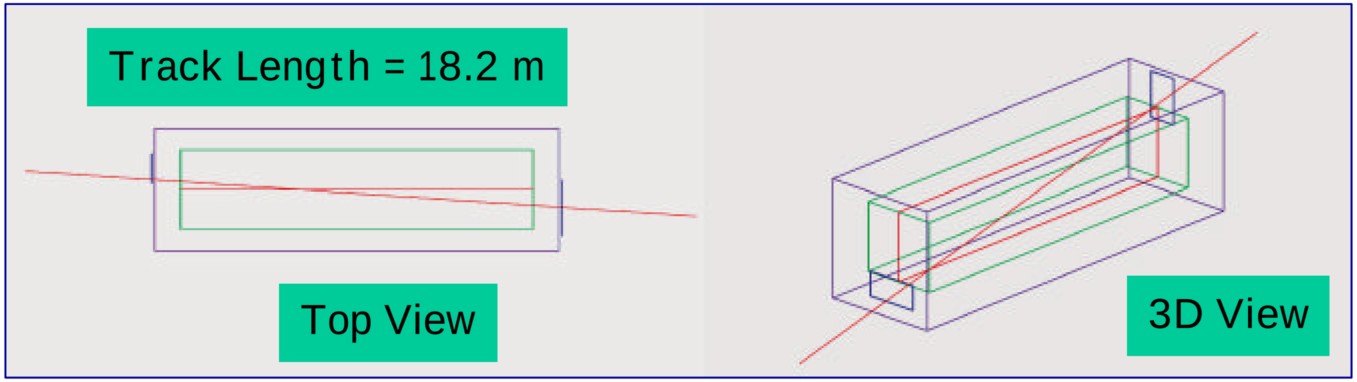


T_e=36.2 MeV
Range=15.4 cm

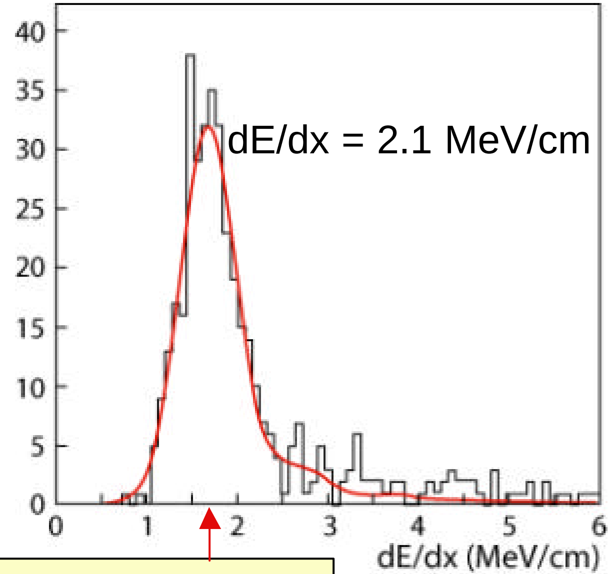
Long longitudinal muon track crossing the cathode plane



~ 6000 points in each of the 3 readout planes !

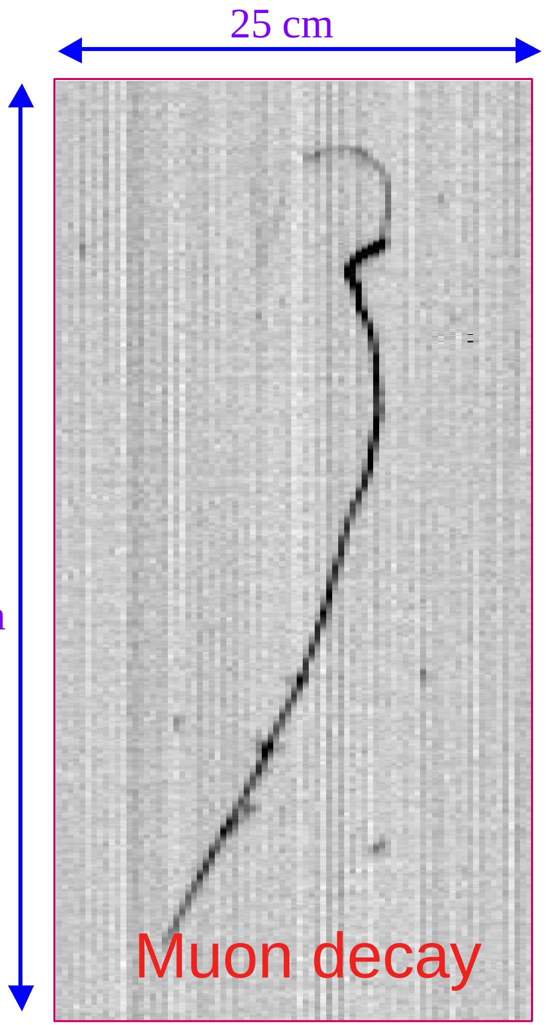


3-D reconstruction of the long track

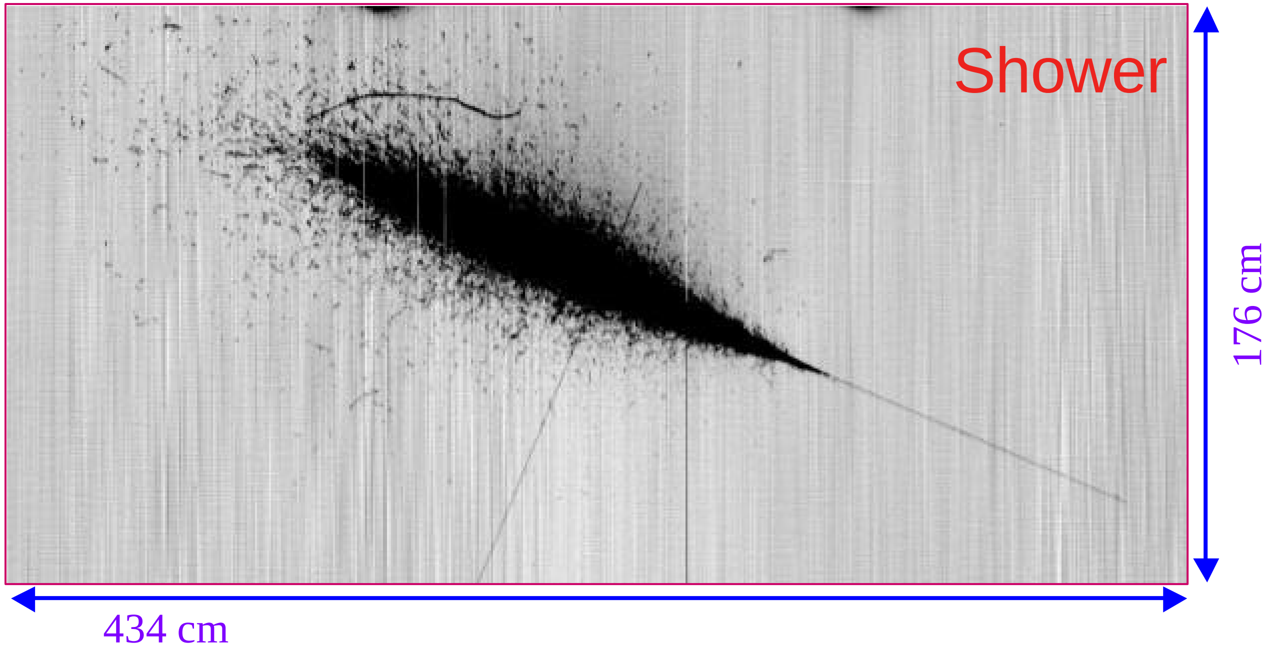


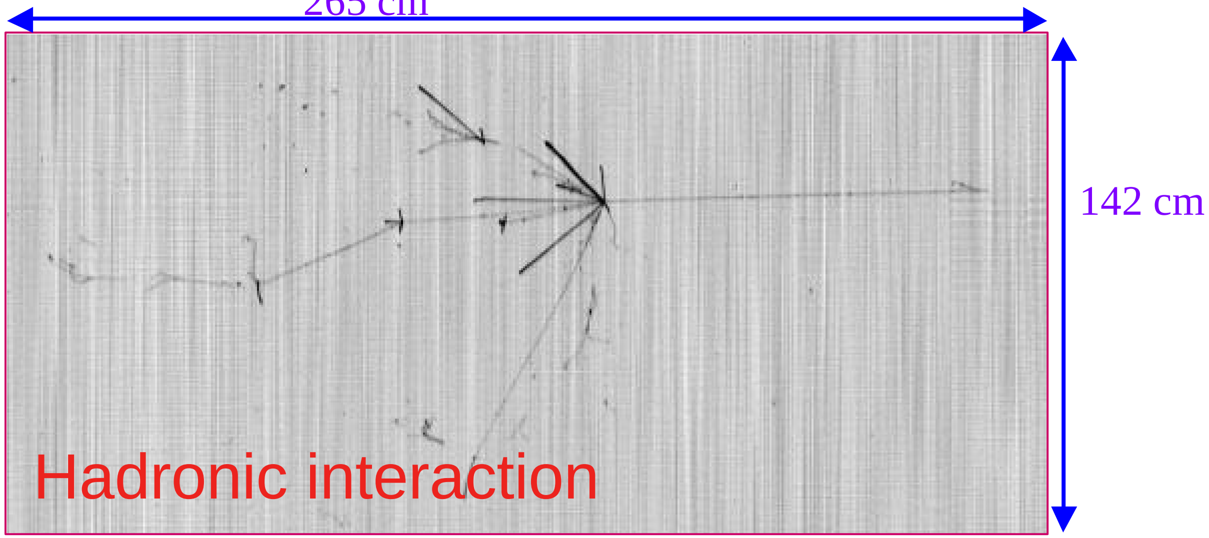
dE/dx distribution along the track

Cosmic ray interactions



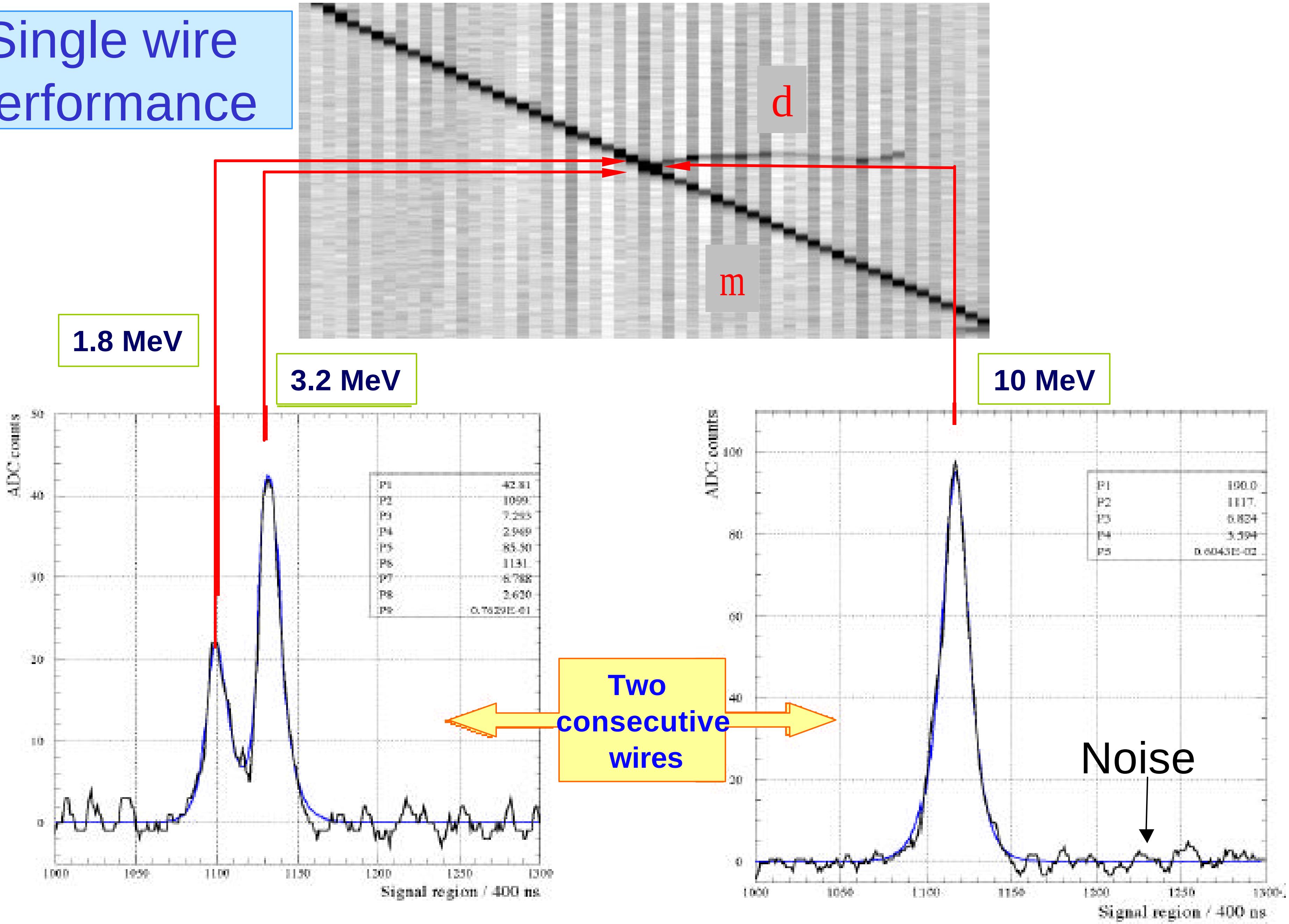
Run 960, Event 4 Collection Left





Run 308, Event 160 Collection Left

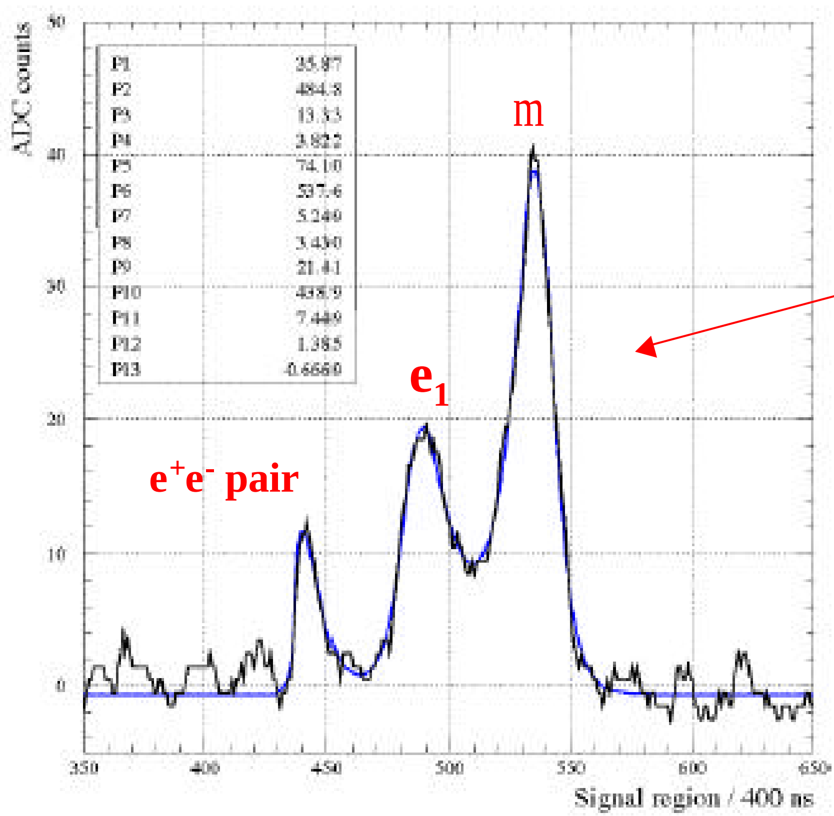
Single wire performance



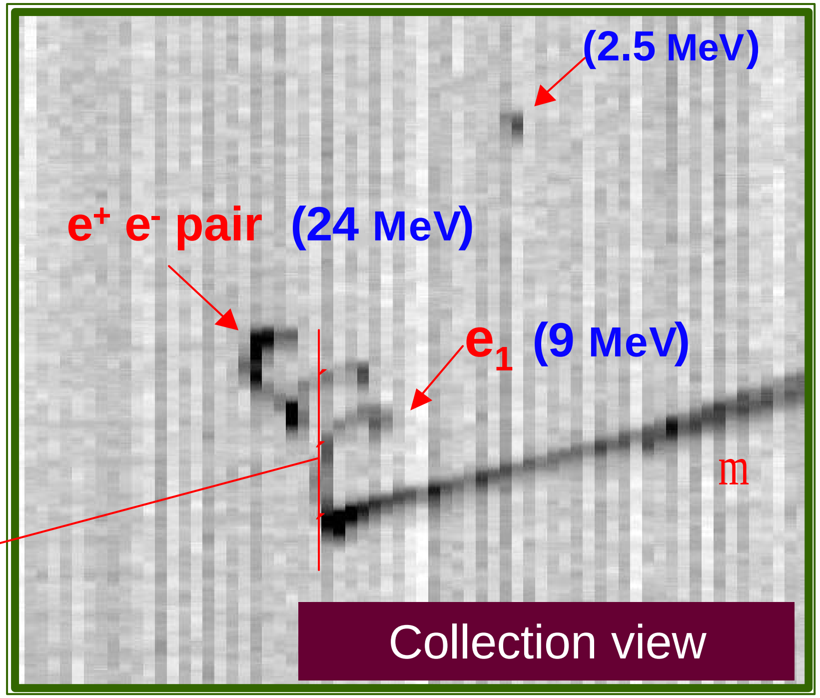
Threshold above noise ~ 200 keV

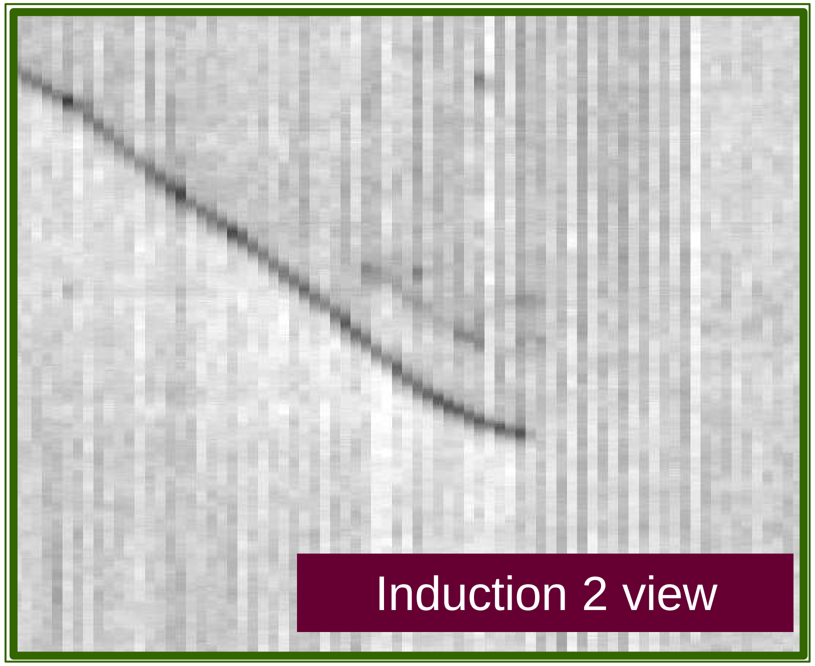
Bremsstrahlung
+ pair-production

Run 975, Event 163



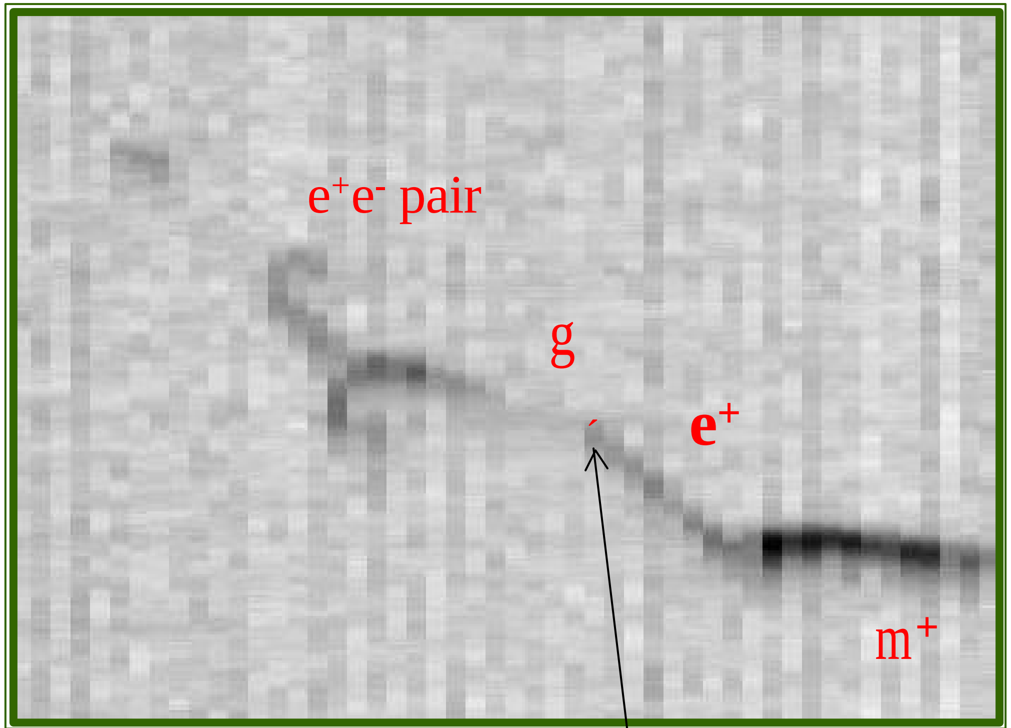
Fitted signal shapes
on single wire





In-flight annihilation of positron

~20% of positrons from μ decays expected to annihilate before stopping

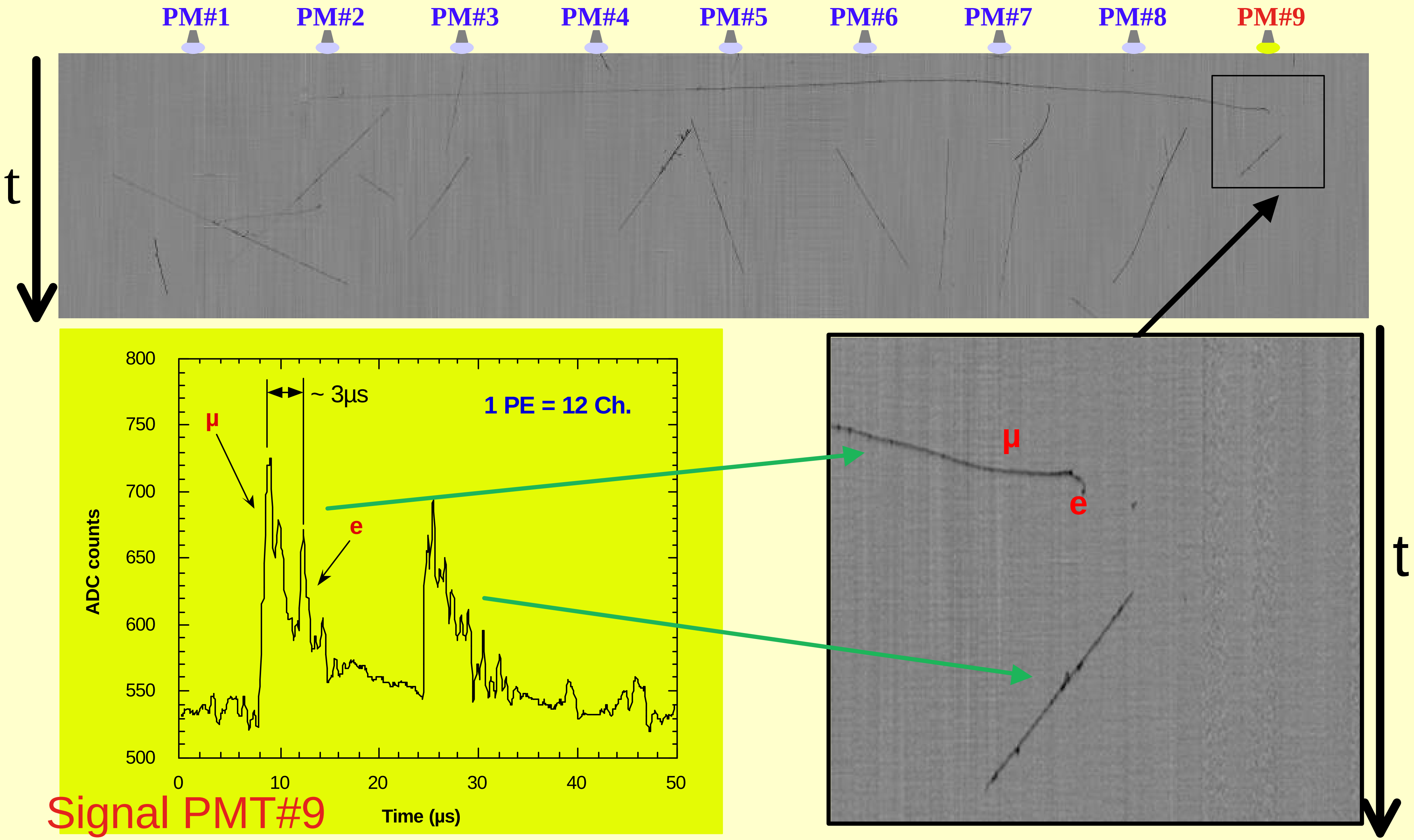


Collection view

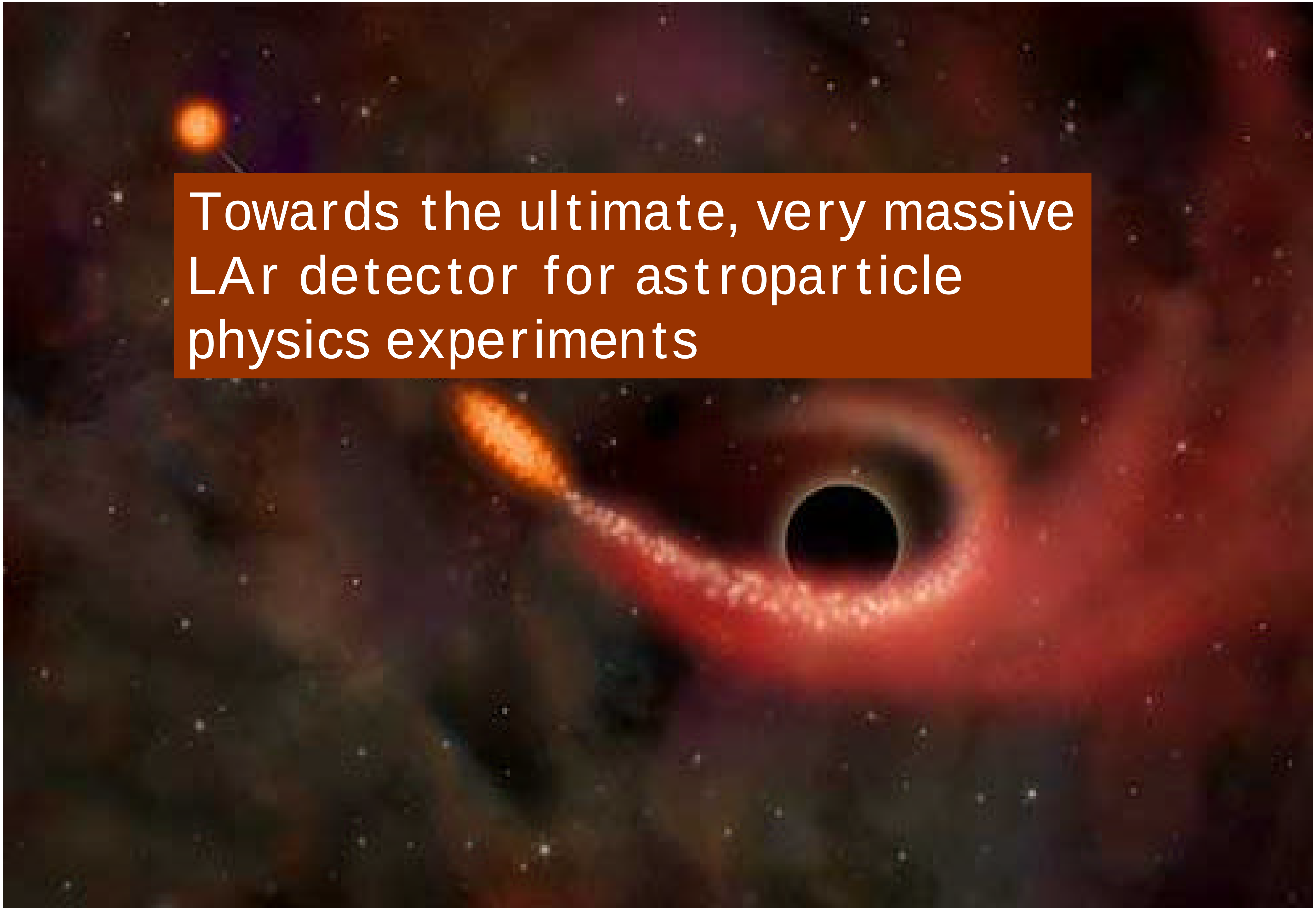
annihilation point

Induction 2 view

Scintillation light readout

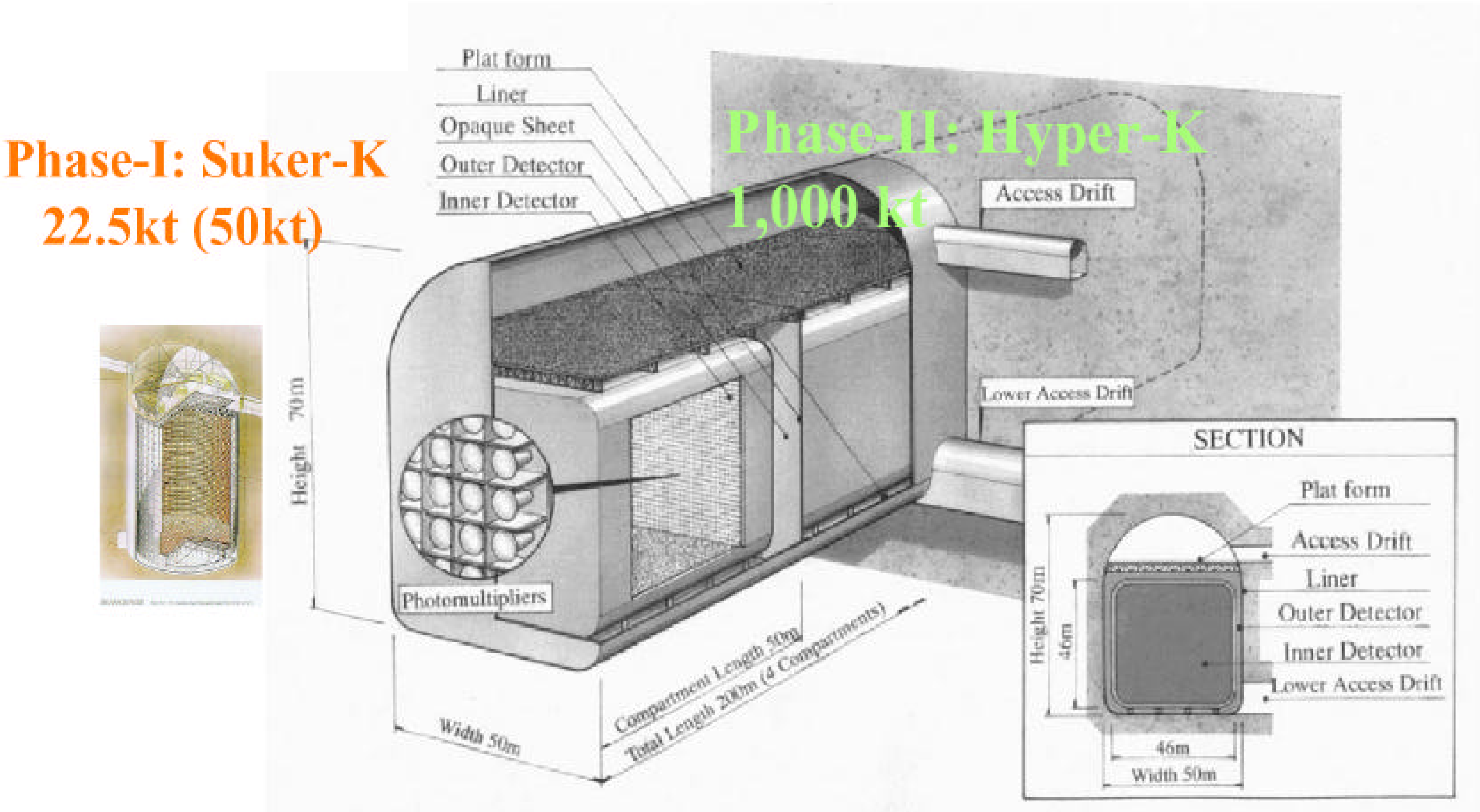


Towards the ultimate, very massive LAr detector for astroparticle physics experiments

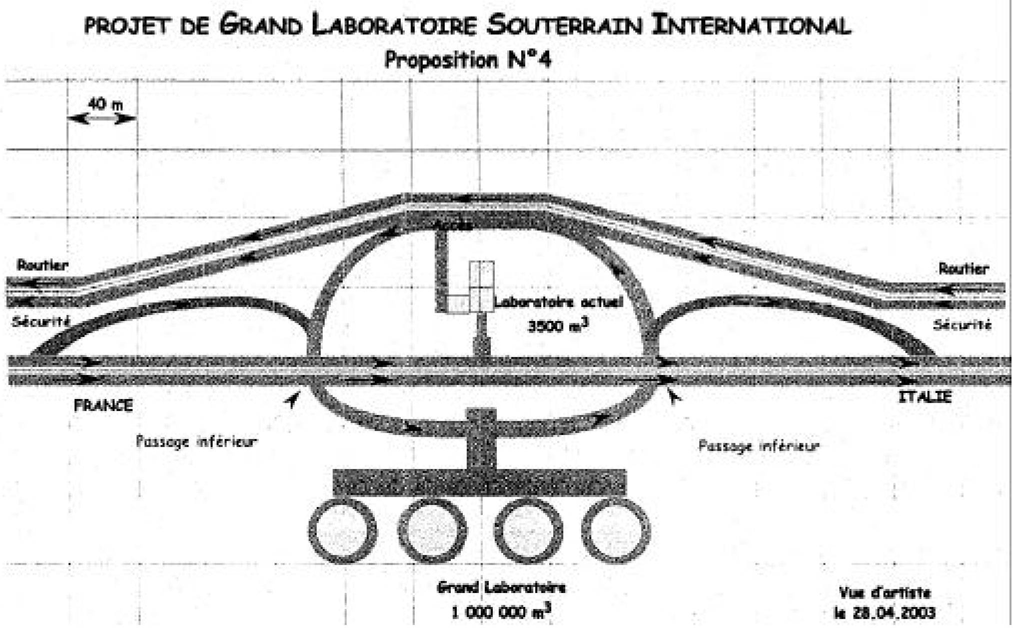


Giant water Cerenkov (up to 1Mton)

- Widely perceived as a “straightforward” extension of SK (?)
- Many “proposals”, e.g., Hyper-K, UNO
- Many sites, e.g., Frejus, Kamioka, Homestake, etc.
- Physics case is “broad”: proton decay, neutrino properties, galactic supernovae, …



e.g.: the programme in Frejus: Superbeam or beta-beam from CERN (130 km)



"Cooperation agreement"
between
French (IN2P3/CNRS, DSM/CEA)
and Italian (INFN) Institutions

....

« The DSM, IN2P3 and the INFN agree to prepare the design of a very Large Underground Laboratory in the new Fréjus tunnel, with complementary features with respect to the Gran Sasso laboratory, to be submitted as a joint proposal to the French and Italian governements.

The institutions aim at associating the Fréjus and Gran Sasso laboratories in a single entity, a European Joint Laboratory, open to the world scientific community to carry out advanced experiments in particle, astroparticle and nuclear physics in the coming decades, on topics such as matter stability, neutrino mixing and mass, stellar collapses and nuclear astrophysics »

Detector options: 4 x 250 kton Cerenkov tanks ? ... a 100-200 kton LAr detector ?

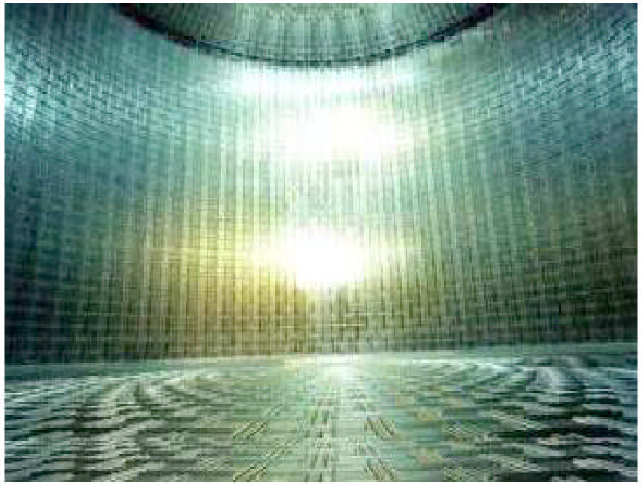
OTHER SITES MAY WELL BE CONSIDERED FOR VERY LARGE DETECTORS

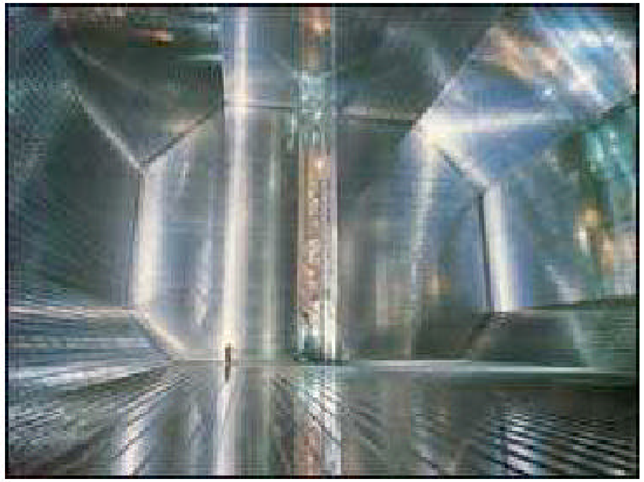
- Astroparticle physics (without beam) interesting 'per se'
- Investment for the detector may be comparable to the beam facility
- Existing underground sites like mines, etc.

An effective alternative: a very massive LAr detector

- Can one extrapolate LAr technology to > 100 kton detector ?
- Ultra-pure liquid Argon is cheap and industrially available.
- Cryogenic tanks for Liquefied Natural Gas (LNG) are industrially well developed products with considerable sizes. Heat leaks are small (~ 5 W/m^2)
- Ideas being developed:

See e.g.:





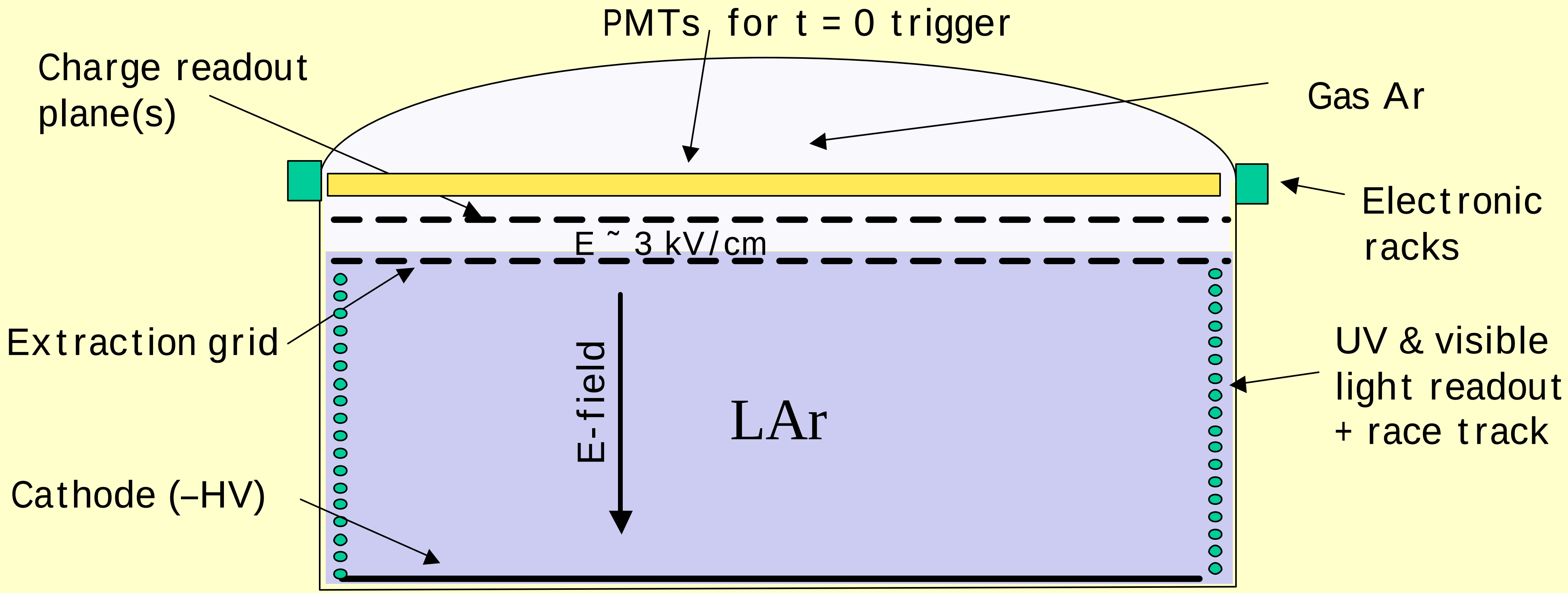
Experiments for CP violation: a giant liquid Argon scintillation, Cerenkov and charge imaging experiment.

A.Rubbia, Proc. II Int. Workshop on Neutrinos in Venice, 2003, hep-ph/0402110

Liquid Argon Imaging Technology.

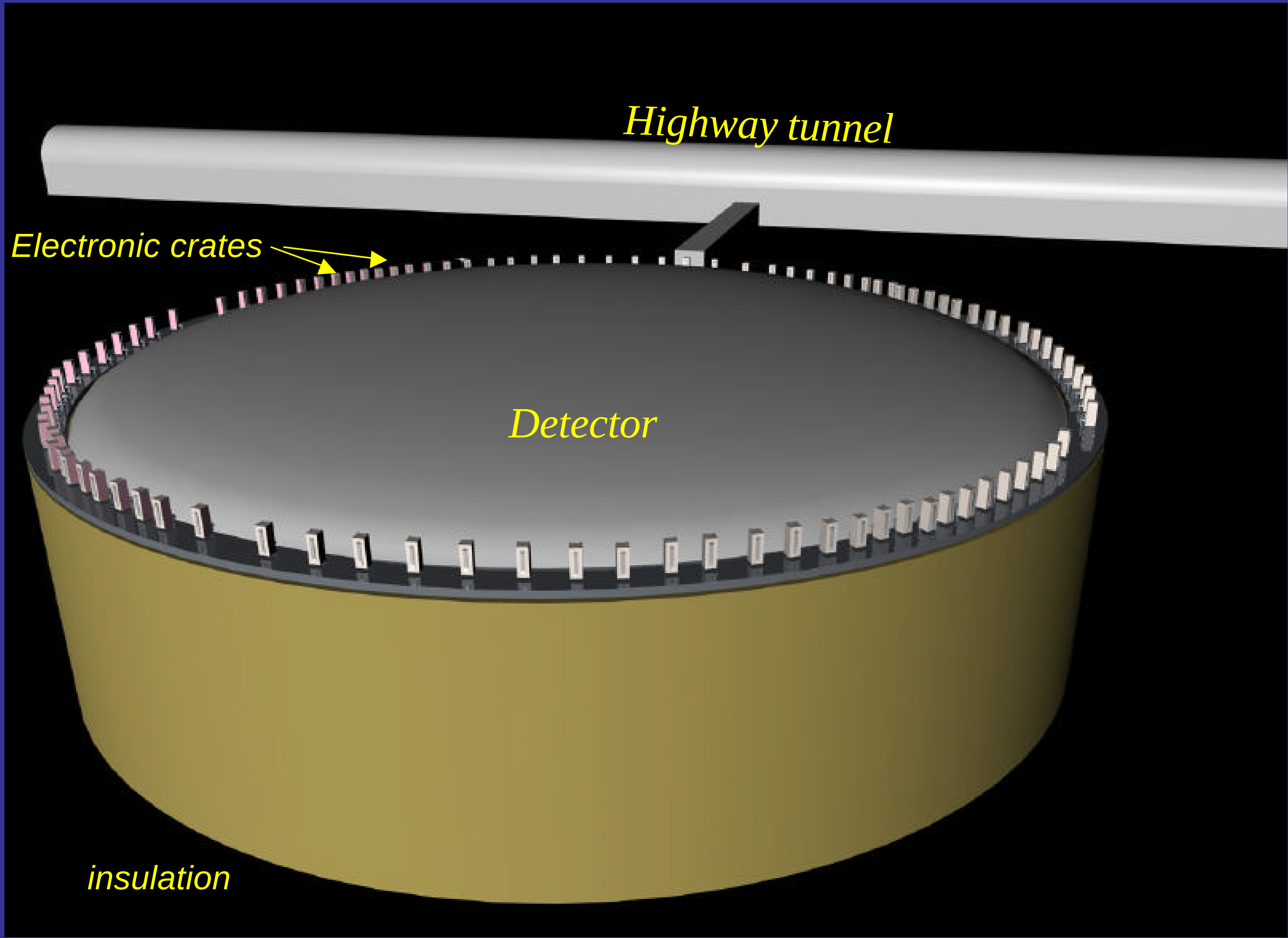
C.Rubbia, talk at the SLAC Experimental Seminar February 17, 2004.

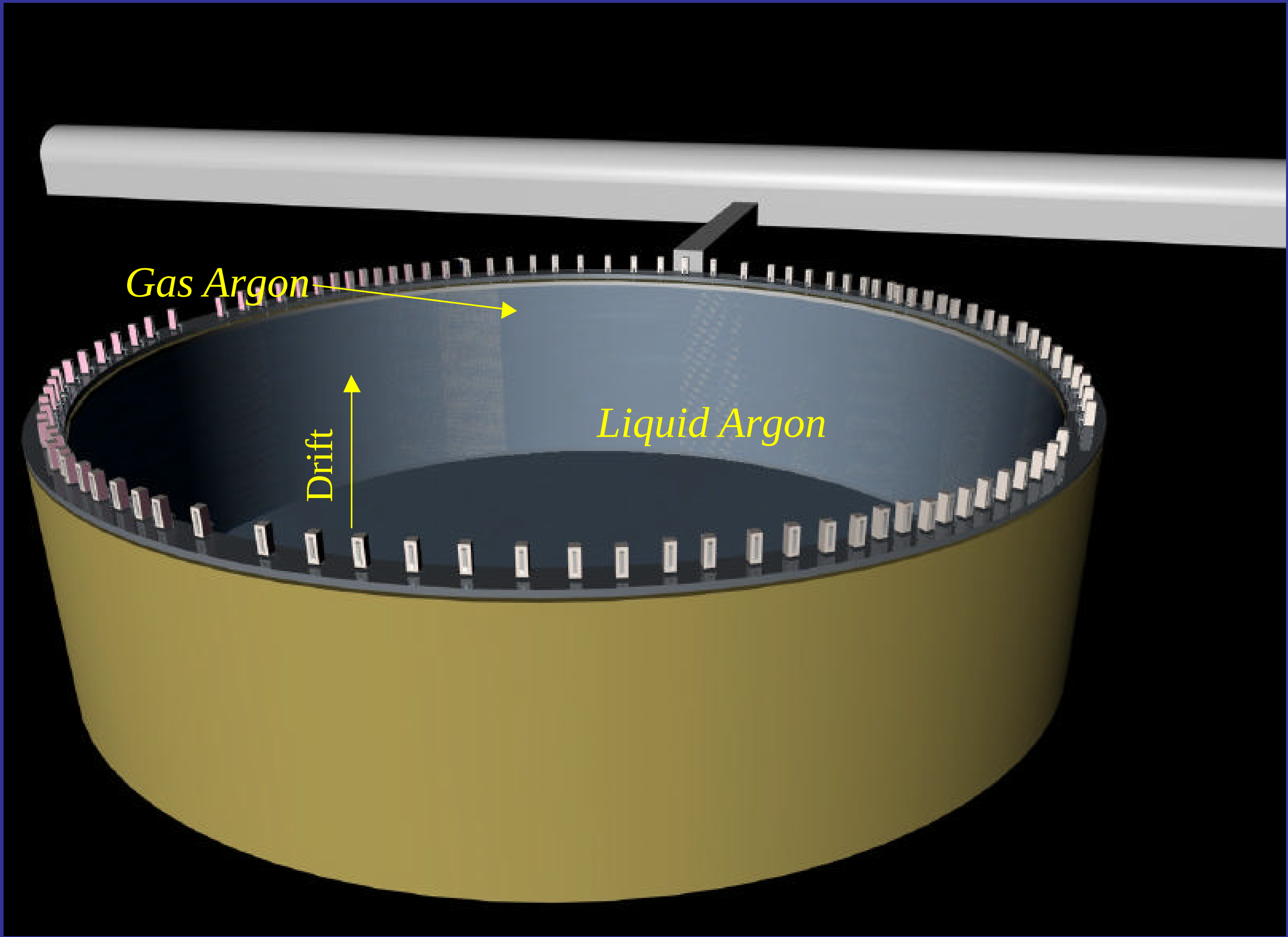
A 100-200 kton LAr detector: conceptual design



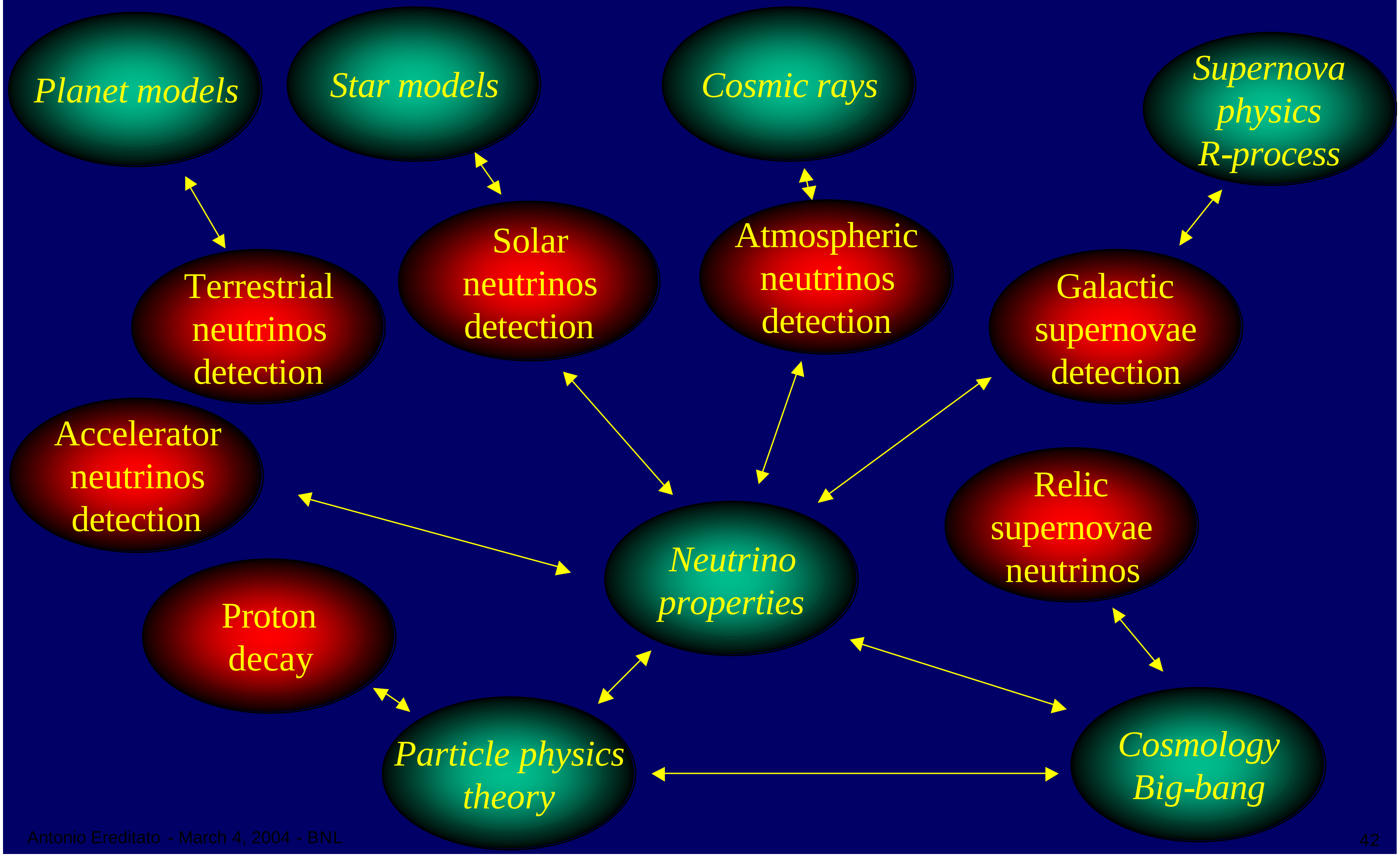
- 70-120 m diameter, 15-20 m height, ~ 100000 readout wires
- In situ cryogenic plant, 5 W/m^2 heat input, continuous re-circulation (purity)
- Filling speed (100 kton): 150 ton/day → 2 years to fill
- E= 500-1000 V/cm V_O= 750-1500 kV, drift time ~ 10 ms
- Max charge attenuation/required multiplication: ~ factor 100 (e.g. thin wires/pads)
- Same detector: charge imaging, scintillation, Cerenkov light

Highway tunnel laboratory option

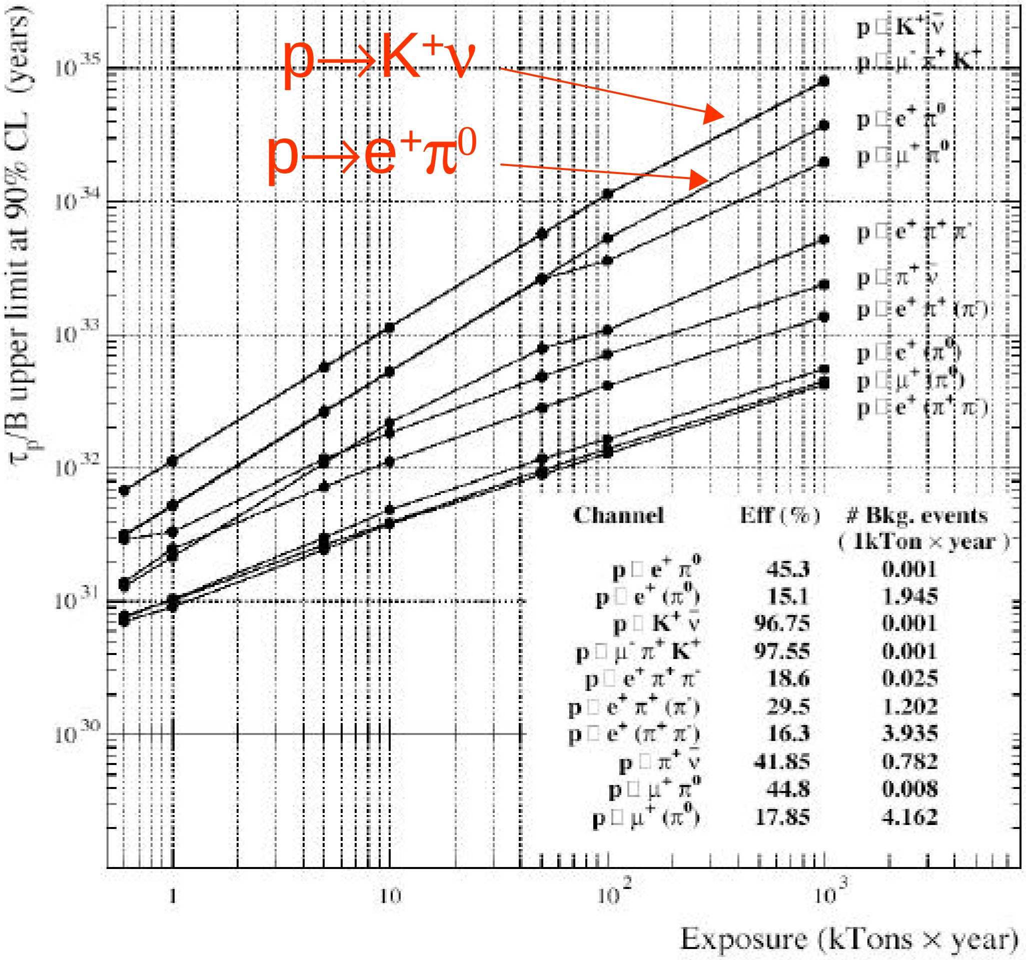



Gas Argon
Drift
Liquid Argon

Physics


Planet models
Star models
Cosmic rays
Supernova physics R-process
Terrestrial neutrinos detection
Solar neutrinos detection
Atmospheric neutrinos detection
Galactic supernovae detection
Accelerator neutrinos detection
Neutrino properties
Relic supernovae neutrinos
Proton decay
Particle physics theory
Cosmology Big-bang

Proton decay: sensitivity vs exposure

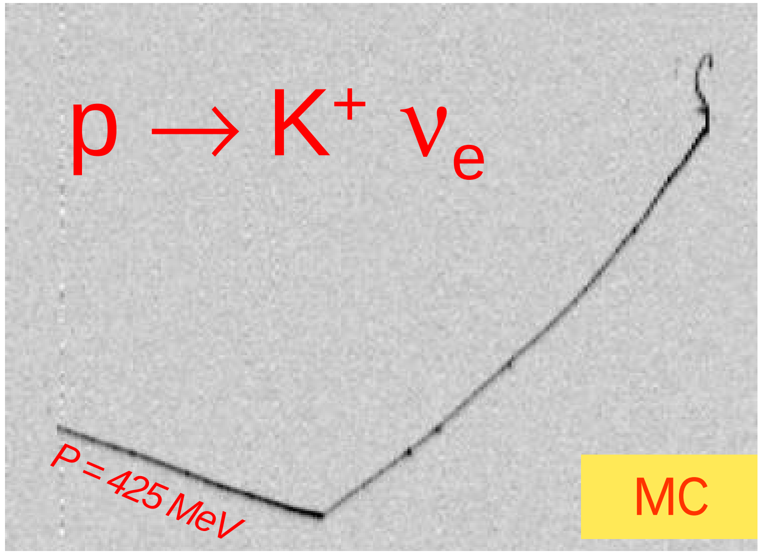


Channel	Eff (%)	# Bkg. events (1kTon × year)
$p \square e^+ \pi^0$	45.3	0.001
$p \square e^+ (\pi^0)$	15.1	1.945
$p \square K^+ \bar{\nu}$	96.75	0.001
$p \square \mu^- \pi^+ K^+$	97.55	0.001
$p \square e^+ \pi^+ \pi^-$	18.6	0.025
$p \square e^+ \pi^+ (\pi^-)$	29.5	1.202
$p \square e^+ (\pi^+ \pi^-)$	16.3	3.935
$p \square \pi^+ \bar{\nu}$	41.85	0.782
$p \square \mu^+ \pi^0$	44.8	0.008
$p \square \mu^+ (\pi^0)$	17.85	4.162

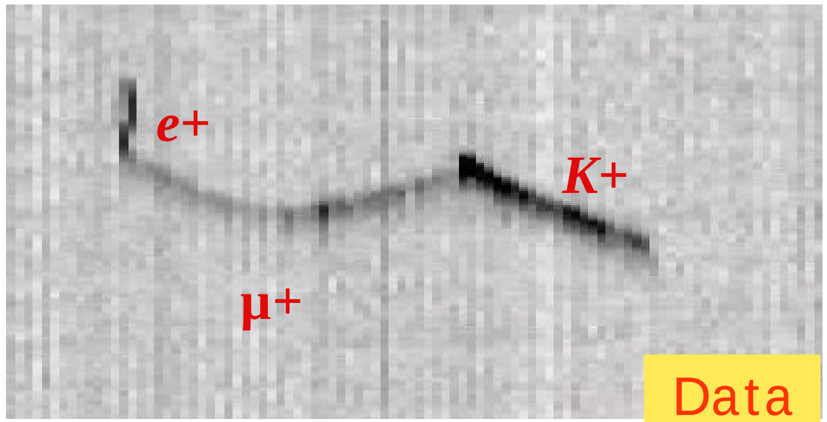
6×10^{34} nucleons (100 kton) $\Rightarrow$

t_p/Br > 2 10^{34} years $\times$ T(yr) ´ e @ 90 CL

65 cm



"Single" event detection capability



T600: Run 939 Event 46

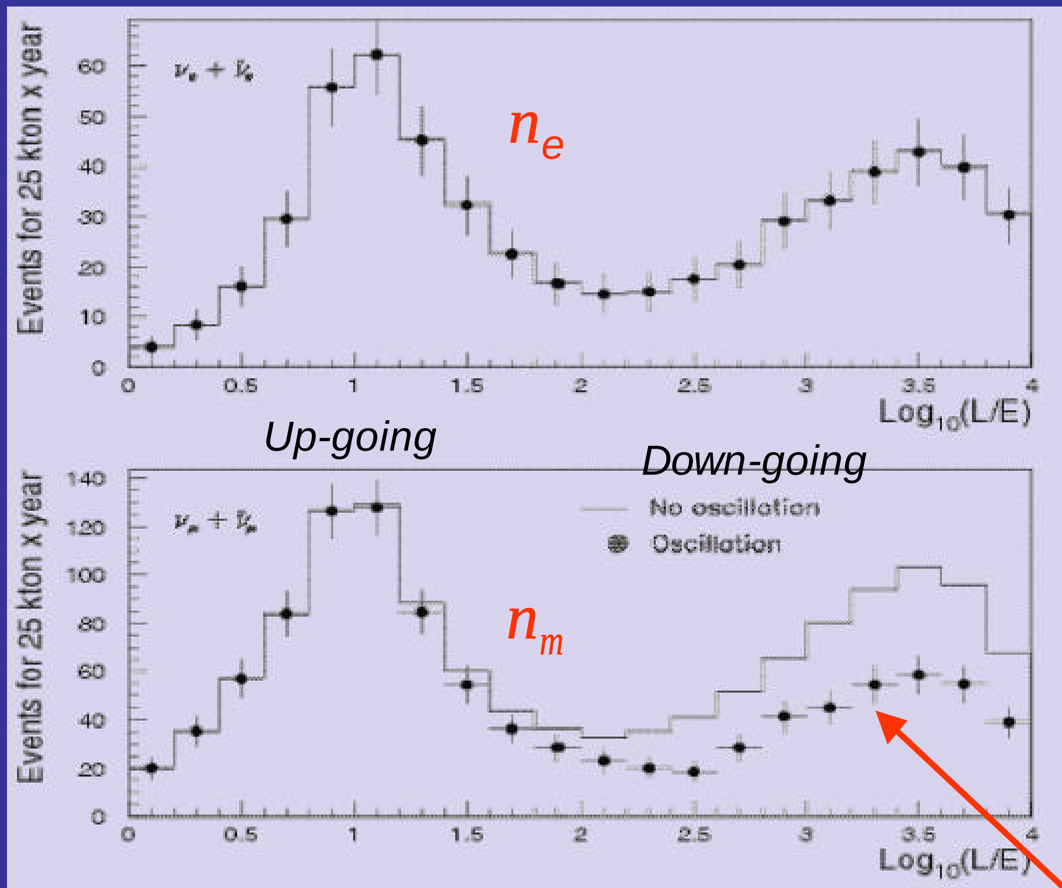
Atmospheric neutrino events

The LAr detector will provide:

- ✓ Observation of atmospheric neutrino events with high quality
- ✓ Unbiased, systematic free observation
- ✓ Excellent energy and angular reconstruction

Event rate in 1/10 of a year for 200 kton

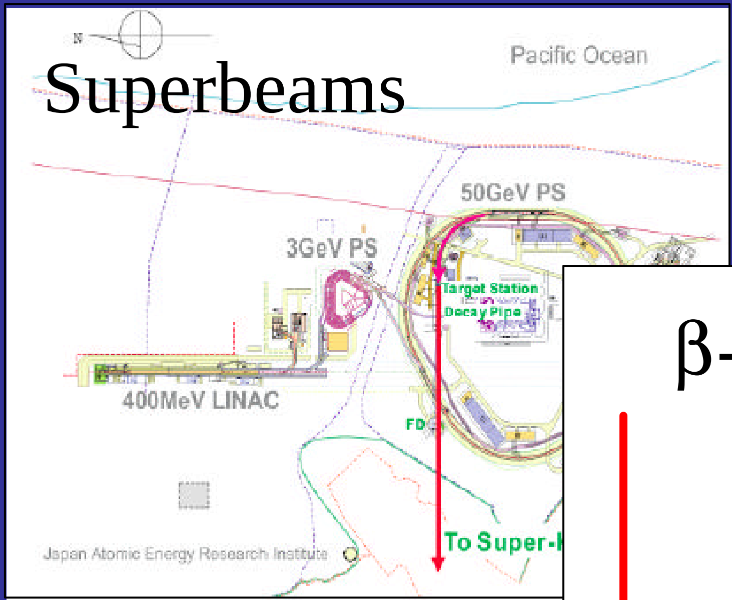
8 years of ICARUS T3000 operation



log_{10}(length/energy) →

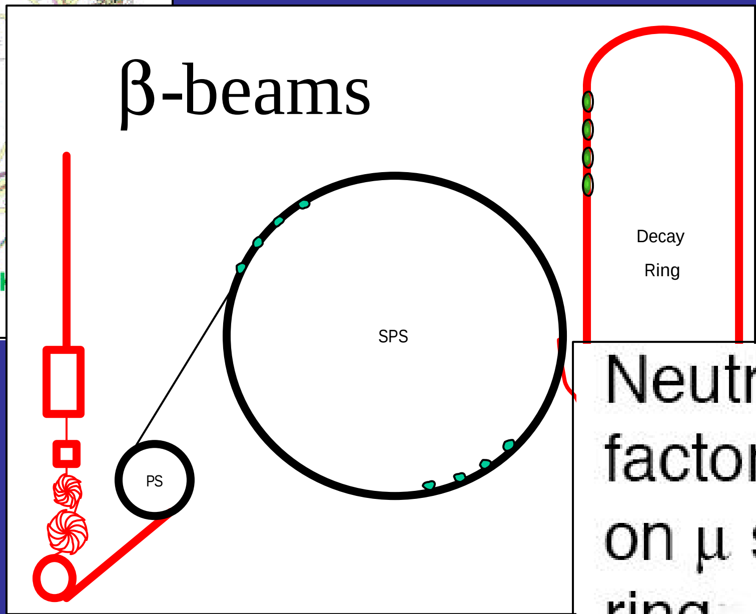
Effect of oscillations

Accelerator neutrinos



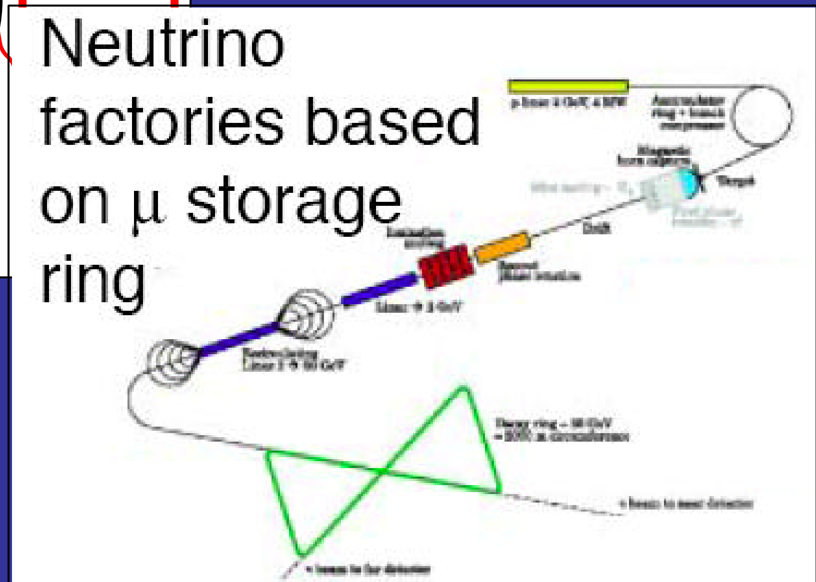
$$p^{\pm} \rightarrow m^{\pm} \overset{(-)}{n}_{m}$$

Select focusing sign



$$^{Z}A \rightarrow {}^{Z\mp1}A \; b^{\pm} \; \overset{(-)}{n}_{e}$$

Select ion



$$\left.\begin{array}{l} m^{-} \rightarrow e^{-}\bar{n}_{e} n_{m} \\ m^{+} \rightarrow e^{+} n_{e} \bar{n}_{m} \end{array}\right\}$$

Select ring sign

Events for 100 kton detector mass

Number of targets for nucleon stability:

6×10^{34} nucleons $\Rightarrow$ $\tau_p/\mathrm{Br} > 10^{34}$ years $\times$ T(yr) $\times \varepsilon$ @ 90 CL

Low energy Super-Beams or beta-beams:

460 ν_μ CC per 10^{21} 2.2 GeV protons (real focus) @ L = 130 km

15000 ν_e CC per 10^{19} ^{18}Ne decays with γ=75

Atmospheric:

10000 atmospheric events/year

100 ν_τ CC /year from oscillations

Solar:

324000 solar neutrinos/year @ $E_e > 5$ MeV

Supernova type-II:

20000 events @ D=10 kpc

Conclusions

- Ultra-pure liquid Argon is now well mastered industrially. Events of remarkable quality, excellent energy and 3D angular reconstruction are routinely produced. The detector is self-triggering and continuously sensitive.

- A 600 ton (ICARUS T600) detector has been operational since a couple of years and it is going to be commissioned at LNGS for underground operation. R&D completed and industrialization phase addressed. Real events already available.

- ICARUS at LNGS: the most important milestone for the technology; test-bed with 3 kton of liquid Argon in a difficult underground environment: simultaneous detection of cosmic events and CNGS beam neutrinos.

- Signal multiplication after extraction in the gas and the industrial technology of LNG allow to conceive a very massive (~ 100-200 kton) LAr detector for cosmic and LBL neutrinos, at a cost comparable to a Mton water Cerenkov detector but with an unparalleled spatial and energy resolutions and event reconstruction capabilities.